AD-A116 308 AMERICAN AIRLINES INC FORT WORTH TX F/G 5/9
WIDE-ANGLE, MULTIVIEWER, INFINITY DISPLAY SYSTEM.(U)
JUN 82 I WHYTE, A W ZEPF F33615-79-C-0002
UNCLASSIFIED AFHRL-TR-81-27(1) NL

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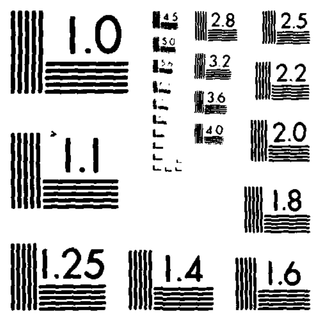

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AFHRL-TR-81-27(I)

AIR FORCE

HUMAN

RESOURCES

AD A116308

WIDE-ANGLE, MULTIVIEWER, INFINITY DISPLAY SYSTEM

By

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June 1982

Final Report

LABORATORY

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AIR FORCE SYSTEMS COMMAND
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFHRL-TR-81-27(I)	2. GOVT ACCESSION NO. [illegible]
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): WIDE-ANGLE, MULTIVIEWER, INFINITY DISPLAY SYSTEM	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Ian Whyte; A. W. Zepf	8. CONTRACT OR GRANT NUMBER(s): F33615-79-C-0002
9. PERFORMING ORGANIZATION NAME AND ADDRESS: American Airlines, Flight Academy, American Airlines Plaza, Fort Worth, Texas 76125	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61101F; ILIR0036
11. CONTROLLING OFFICE NAME AND ADDRESS: HQ Air Force Human Resources Laboratory (AFSC), Brooks Air Force Base, Texas 78235	12. REPORT DATE: June 1982
	13. NUMBER OF PAGES: 91
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Operations Training Division, Air Force Human Resources Laboratory, Williams Air Force Base, Arizona 85224	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Technical support was provided by Rediffusion Simulation, LTD., Gatwick Road, Crawley, Sussex, United Kingdom.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

collimation optics
computer generated imagery
dipvergence
field of view
geometric distortion
potassium di hydrogen phosphate (KDP) light valve
liquid crystal light valve
mirror fabrication
oil film light valve
resolution
scan laser
viewing volume
visual display systems
visual simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study examined the design specification for a wide-angle infinity display system with minimal distortion, convergence, dipvergence, and collimation errors for use on wide-body-aircraft simulators. The report includes a recommended final design specification; a survey of potential fabrication technologies for projector, screen and large mirrors; an approach to fabrication of a large display system; and finally, assembly and alignment techniques of mirror segments for a large display. (Note: Dipvergence refers to vertical movement of eyes up and down as opposed to side to side.)

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SUMMARY

Objective

The primary objective was a specification for a wide angle, multiviewer, infinity image display system for use in flight simulators for wide-body aircraft. Additional objectives were (a) to survey potential fabrication technologies for screens, projectors and large mirrors; (b) to develop an overall approach for fabricating a large display system; and (c) to investigate techniques for assembling and aligning mirrors for a large display.

Background/Rationale

The Air Force has a requirement for an infinity image display system for use in flight simulators for wide-body aircraft crew training. The system is to provide a realistic out-the-window visual scene to the entire cockpit crew. Two previous studies have recommended that the optical system for such a display use a spherical mirror as the basic collimating element, with a rear projection screen of toroidal shape located above the simulator cockpit. The present study, which is the last phase of the program, is mainly concerned with the development of a specification and an approach to fabricating the proposed display system.

Approach

The approach was to optimize the final optical design considered in the two previous studies. In parallel with the optimization work, mirror, screen, and projector technology was surveyed, and methods of fabricating the display system were developed. The system mechanical design was accomplished, and mirror samples were manufactured for the assembly demonstration. Finally, the system was reviewed, and a trade-off study was performed to identify an alternative system which could satisfy the Air Force performance goals and still fit on an existing motion platform.

Specifics

In the final design, the two main areas addressed were the design of the collimation and projection optics. The layout of the system was based on the findings of the two previous studies utilizing a rear screen projection system and spherical mirror collimating optics. A ray tracing program was used to determine the size and shape of the screen required. Distortion and decollimation were studied and a design for minimum mirror size was determined through use of the ray trace program. The analysis program was validated by checking against a different ray trace program on another computer. The results were within the specification of 3 milliradians except for a few locations at the edge of the field of view. When compared with the two preceding studies, the results were within .2 milliradian of the convergence and divergence figures.

Projectors of various types were also investigated. The advantages and disadvantages of each were considered, and the best candidates were selected for further analysis. The three top candidates were the single tube oil film light valve, the Pockel effect light valve, and the scanned laser projectors. The oil film light valve projector does not meet the Air Force design goals for resolution; however, it currently is available, and has been used on many systems to date. The other two projectors (which still are under development) will meet the specified design goals. Of these two, the scanned laser projector is preferred since only one is required and no Fresnel layer is required on the screen. The Pockels projector will require a Fresnel rear projection screen coating.

Various screen materials were also investigated, and methods of applying the Fresnel lenticulations were determined. Due to the curved surface of the screen, application of a Fresnel layer is difficult. An alternative is to machine the Fresnel lenticulations directly into the screen structure, which would require some tooling. To eliminate the problems associated with the Fresnel layer, use of the scanned laser projector was recommended.

The collimating mirror vendor analysis was accomplished by investigating different methods of manufacture. Methods considered were machined and polished glass, cervit and plastic slumped glass, and replication in plastic and metal with a lightweight bonded backing. The slumped glass, metal replicated, and plastic replicated mirrors were shown to have clear technical advantages over the others because of the large size required. Of these three, slumped glass could be made in large sections, but is very heavy. The metal replicated mirror is feasible, but is fairly heavy and, due to the limited size of manufacture, would require many sections with a large support structure. The plastic replicated mirror, on the other hand, has the clear advantages of lighter weight and ease of assembly. Mirror joining techniques, therefore, were developed around the plastic replicated mirror concept and the system mechanical design incorporates the lightweight replicated mirrors and the laser projector.

The inertial characteristics of the visual system required to meet the original Air Force design goals exceeded the capability of a standard simulator motion platform. Therefore, a trade-off analysis was completed to determine which physical parameters could be reduced to permit the system to be mounted on a motion platform without an unacceptable compromise of visual system performance. It was concluded that for a 180 + x 50 + field of view, all other parameters could be met with a 14.75-foot radius mirror, which would allow the system to be used on a standard motion platform.

Conclusions/Recommendations

It was concluded that a complete wide-angle, multiviewer, infinity display system could be developed to satisfy all of the Air Force design goals. However, such a system would be too large and heavy to function properly on a standard flight simulator motion platform and also would require development of a new projector subsystem. The specification for an alternative system with somewhat relaxed design goals was recommended. This system would not only fit a standard motion platform, but could utilize the existing state of the art in projector development.

PREFACE

The purpose of this study was to determine the feasibility of fabrication and to evaluate the potential optical performance of an optical display to provide the out-the-window scene for a multi-crewmember cockpit. This study was conducted by the Operations Training Division, Air Force Human Resources Laboratory, Air Force Systems Command. The study is in support of Research Objective 1.2.8 Operator Performance Assessment, which in turn supports Technology Planning Objective G03, Air Combat Tactics and Training, Specific Objective 1d, Aircrew Training Technology Applications, and will eventually complement the development of the refractive optical display (Work Unit 1958-01-11). 1Lt Michael J. Jasinski is the work unit monitor for ILIR-00-36. The research and development is being directed by the American Airlines Program Manager, Mr Al Zepf, with technical support provided by Rediffusion Simulation, LTD, under their Program Manager, Mr Ian Whyte.

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1.0 SUMMARY OF PREFERRED DISPLAY SYSTEM

1.1 Introduction. The Air Force has defined a requirement for an infinity image display system for use in flight simulation for wide-bodied aircraft. This requirement is to provide the out-the-window scene to the entire crew in the cockpit of the simulator. This study is concerned with defining the feasibility of such a display system and identifying whether current technology can produce the display, preferably one that can be mounted on available motion systems.

As discussed in two preceding reports, Shaffer, L. W. & Wadelich, J. A., Wide-Angle Multiviewer Infinity Display Design, dated September 77 and Rhinehart, R. M., Wide-Angle Multiviewer Infinity Display Design, dated December 77, it had been decided that the optical system for such a display should use a spherical mirror as the basic collimating element, with a rear projection screen of toroidal shape located above the simulator cockpit.

This report describes the present phase of development, which is mainly concerned with an approach to fabricating the display system. As a necessary prelude to defining the fabrication technology, a finally optimized optical design was carried out.

Section 2 of this report describes the preferred optical design and the design process, including interpretation of the Air Force specification. Section 3 is concerned with a discussion on current video projector technology and how individual projection devices will interface with the collimation optics. This section also identifies the most compatible projection devices and how they affect the required rear projection screen characteristics. Section 4 is concerned with the identification of a suitable rear projection screen vendor and screen fabrication techniques. Section 5 describes the current situation with regard to fabrication of a suitable collimating mirror. Section 6 describes the preferred fabrication and assembly methods and the results of the demonstration of assembly methods. Section 7 is concerned with the overall mechanical design of the complete collimating display. Section 8 is a discussion of possible trade-offs against the original Air Force specification.

1.2 Summary of Preferred Display System. The display system described in this report was designed with a goal of meeting the following performance specifications:

Performance Specifications. The following list of specifications are considered to be design goals for this effort, although in some cases minimum requirements are stated. The previous design studies have indicated that some specifications cannot be met for the entire field of view. Necessary trade-offs are discussed in the text.

a. Viewing Volume. 5 Ft. (1.52 m) (Lateral) X 3 Ft. (0.91 m) (longitudinal) X 1-1/2 Ft. (0.46 m) (vertical) with the bottom plane at the minimum pilot eye height and the forward plane at the maximum forward pilot position. While it is desirable that the following design goals be met throughout this volume, the minimum required viewing volume to which the following goals apply consists of 6 inch (0.152 m) radius spheres centered on the pilot and co-pilot eye points, which for the purpose of this effort are located 6 in X 6 in X 6 in (0.152 m X 0.152 m X 0.152 m) into the viewing volume from the lower front corners. Additional potential viewing locations behind the pilot and co-pilot for a navigator or instructor pilot shall also be considered but are of secondary importance.

b. Field of View. Continuous 180° horizontal and 60° vertical. Realistically, the cross-body view from the pilot or co-pilot eye point is limited by the cockpit windows to about 20° vertically. Thus, a reduced field of view which accounts for cockpit geometry may be developed. A minimum acceptable design would meet the design goals for the graduated field of view, with 60° vertical fields in adjacent windows, decreasing to 20° vertical fields in cross-body windows.

c. Geometric Distortion. Less than 5% of picture height (fraction of full field angle) throughout the field of view and anywhere within the viewing volume.

d. Collimation Error. Zero convergence to 3 milliradians divergence and 3 milliradians dipvergence.

e. Resolution. 4.0 arc minutes per line center; 6 arc minutes per line corner; assuming three 1,000 scan line and 1,000 TV line resolution television inputs.

f. Highlight Brightness. 6 foot-lamberts minimum.

g. Brightness Variation. Less than 50% over the entire field of view.

h. Contrast Ratio. 20:1, assuming 25:1 from the television input.

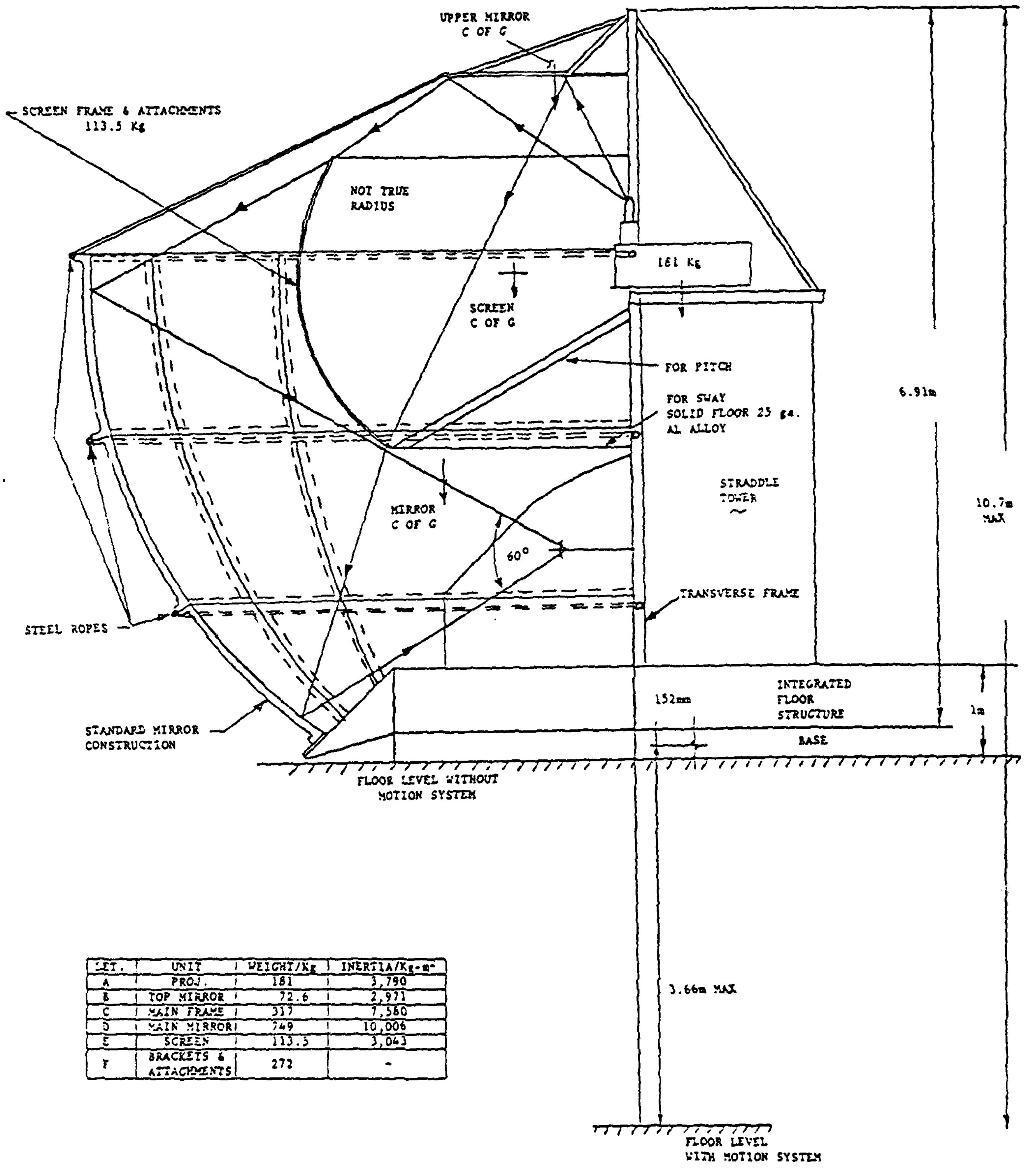
i. Joints. If the display is mosaicked, less than a 5 arc minute gap in the imagery. This applies at joints between mirror segments.

j. Image Registration. If the display is mosaicked, the discontinuity of the image across a joint shall be less than 10 arc minutes when viewed within the viewing volume. This applies at joints between the images provided by separate projectors as well as at joints between mirror segments.

k. Color. The optics shall be color corrected with minimal color shift and minimal color variation across the field of view.

l. Mapping. As a design goal, the system shall provide a linear image to the pilot using a linearly scanned television image input device, with electronic raster distortion utilized to correct small amounts of distortion (less than 10%).

A mechanical layout of the preferred system to meet the above specification as a designed goal is shown in Figure 1. As can be seen, the display system is exceedingly large, and even using lightweight bonded structures for the basic



LET.	UNIT	WEIGHT/Kg	INERTIA/Kg-m²
A	PROJ.	181	3,790
B	TOP MIRROR	72.6	2,971
C	MAIN FRAME	317	7,560
D	MAIN MIRROR	749	10,006
E	SCREEN	113.5	3,043
F	BRACKETS & ATTACHMENTS	272	-

FIGURE 1. SIDE VIEW OF MULTIVIEWER MECHANICAL CONFIGURATION

collimating mirror, fabrication is not compatible with standard six axis motion systems. No doubt a motion system could be built to cater to such a display. Some masses and inertias have been calculated to identify the magnitude of the problem.

The preferred optical design gave good geometry correction. With reference to Tables 1 to 8 and Figures 2 to 9, distortion is below 5% in all areas other than the inboard bottom corners which would not be visible through the aircraft cross-body window areas. Convergence errors were all negative and within 3 mr except in the inboard field and on Table 8 where head position was outboard, down, and forward by 0.15 m. Figure 9 and Table 8 both refer to this position which gives the worst distortion and collimation errors of any other position within the nominated head motion envelope. For dipvergence, again the errors were below 3 mr except for the bottom cross-body view.

Vertical distortion correction on the rear projection screen is required and the non-linearity was below 10% for projectors situated at the screen center. Vertical scaling will be required in the low projection position which is best dealt with in the image generator if raster distortion is to be kept below 10%. Vertical scaling is taken care of in the scan laser projector, Figure 10 and the oil film light valve projector, Figures 11 and 12.

Fresnel structure will be required for the projector options shown in Figures 11 and 13, to maintain reasonable display brightness, uniformity and contrast ratio. The construction of a Fresnel screen is difficult but feasible, and at least one vendor was identified who would be willing to accept the task.

Considering the fabrication of the collimating mirror, only one vendor was found to have the technology to produce a large lightweight mirror that had any chance of being fitted on a motion platform. The only other attractive alternative, assuming the simulator would be fixed base, was to use slumped glass mirrors. Table 9 is a summary of the expected display performance compared with the Air Force design goal. Figure 14 gives topographical representation of the geometric errors as seen from the pilot's nominal head projection with the areas of display vignetted by the rear projection screen and a composite window outline taken from a large number of wide-bodied aircraft. Figure 15 is a similar representation of the collimation errors, again from the nominal pilot head position.

TABLE 1

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.0 UP 0.0 FORWARD 0.0

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	2.26	1.54	0.78	0.00	-0.78	-1.54	-2.26	-2.90	-3.43	-3.77	-3.85	-3.61	-3.05
	+20	2.32	1.62	0.84	-0.00	-0.84	-1.62	-2.32	-2.90	-3.36	-3.66	-3.74	-3.52	-2.99
	+10	2.31	1.66	0.88	0.00	-0.88	-1.66	-2.31	-2.79	-3.12	-3.32	-3.35	-3.16	-2.70
	0	2.31	1.71	0.92	0.00	-0.92	-1.71	-2.31	-2.69	-2.87	-2.91	-2.83	-2.61	-2.22
	-10	2.28	1.73	0.93	0.00	-0.93	-1.73	-2.28	-2.56	-2.60	-2.48	-2.25	-1.96	-1.61
	-20	1.66	1.32	0.73	0.00	-0.73	-1.32	-1.66	-1.74	-1.58	-1.27	-0.92	-0.61	-0.38
	-30	0.38	0.43	0.27	-0.00	-0.27	-0.43	-0.38	-0.11	0.32	0.81	1.24	1.49	1.47

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	0.02	-0.07	-0.11	-0.12	-0.11	-0.07	0.02	0.18	0.38	0.56	0.69	0.74	0.72
	+20	0.01	0.06	0.13	0.17	0.13	0.06	0.01	0.06	0.23	0.51	0.83	1.12	1.34
	+10	-0.01	0.23	0.43	0.50	0.43	0.23	-0.01	-0.18	-0.20	-0.01	0.35	0.79	1.21
	0	-0.02	0.37	0.65	0.75	0.65	0.37	-0.02	-0.42	-0.73	-0.83	-0.70	-0.37	0.06
	-10	-0.03	0.42	0.72	0.82	0.72	0.42	-0.03	-0.56	-1.08	-1.51	-1.76	-1.80	-1.66
	-20	-0.03	0.46	0.77	0.87	0.77	0.46	-0.03	-0.68	-1.43	-2.21	-2.95	-3.55	-3.98
	-30	-0.01	0.58	0.93	1.05	0.93	0.58	-0.01	-0.85	-1.90	-3.13	-4.46	-5.78	-6.97

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	-2.17	-2.29	-2.41	-2.46	-2.41	-2.29	-2.17	-2.14	-2.25	-2.49	-2.79	-3.08	-3.33
	+20	-2.20	-2.41	-2.58	-2.64	-2.58	-2.41	-2.20	-2.06	-2.07	-2.26	-2.57	-2.91	-3.21
	+10	-2.17	-2.47	-2.70	-2.78	-2.70	-2.47	-2.18	-1.90	-1.75	-1.81	-2.07	-2.43	-2.79
	0	-2.19	-2.56	-2.83	-2.92	-2.83	-2.56	-2.19	-1.79	-1.48	-1.34	-1.45	-1.74	-2.14
	-10	-2.18	-2.60	-2.89	-2.99	-2.89	-2.60	-2.18	-1.70	-1.25	-0.95	-0.85	-0.99	-1.28
	-20	-1.46	-1.93	-2.24	-2.35	-2.24	-1.93	-1.46	-0.91	-0.36	0.09	0.37	0.42	0.27
	-30	0.02	-0.48	-0.80	-0.92	-0.80	-0.48	0.02	0.62	1.24	1.81	2.23	2.45	2.45

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	1.80	1.38	0.75	-0.00	-0.75	-1.38	-1.80	-1.95	-1.85	-1.58	-1.25	-0.93	-0.64
	+20	1.97	1.44	0.76	-0.00	-0.76	-1.44	-1.97	-2.26	-2.28	-2.05	-1.67	-1.26	-0.88
	+10	2.00	1.40	0.72	0.00	-0.72	-1.40	-2.00	-2.44	-2.65	-2.57	-2.25	-1.78	-1.28
	0	1.87	1.27	0.64	0.00	-0.64	-1.27	-1.87	-2.38	-2.76	-2.92	-2.80	-2.41	-1.85
	-10	1.65	1.10	0.55	0.00	-0.55	-1.10	-1.65	-2.17	-2.63	-2.95	-3.05	-2.86	-2.38
	-20	1.50	0.98	0.49	0.00	-0.49	-0.98	-1.50	-2.02	-2.53	-2.96	-3.23	-3.23	-2.89
	-30	1.36	0.88	0.43	0.00	-0.43	-0.88	-1.36	-1.86	-2.37	-2.82	-3.16	-3.27	-3.03

TABLE 2

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.15 m UP 0.0 FORWARD 0.0

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	6C	75	90
	+30	2.06	1.28	0.47	-0.35	-1.16	-1.94	-2.69	-3.37	-3.93	-4.25	-4.24	-3.85	-3.09
	+20	2.17	1.40	0.53	-0.39	-1.27	-2.06	-2.75	-3.33	-3.80	-4.10	-4.10	-3.75	-3.03
	+10	2.24	1.48	0.57	-0.42	-1.35	-2.14	-2.73	-3.16	-3.46	-3.64	-3.63	-3.35	-2.73
ELEVATION	0	2.32	1.58	0.61	-0.45	-1.44	-2.23	-2.74	-3.00	-3.09	-3.06	-2.95	-2.70	-2.21
	-10	2.36	1.63	0.63	-0.47	-1.49	-2.26	-2.71	-2.84	-2.72	-2.47	-2.19	-1.88	-1.50
	-20	1.78	1.27	0.51	-0.37	-1.17	-1.72	-1.94	-1.82	-1.47	-1.01	-0.59	-0.29	-0.12
	-30	0.52	0.48	0.21	-0.15	-0.45	-0.53	-0.33	0.13	0.77	1.41	1.90	2.08	1.89

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-0.58	-0.66	-0.68	-0.68	-0.66	-0.59	-0.43	-0.17	0.13	0.38	0.52	0.56	0.53
	+20	-0.44	-0.32	-0.22	-0.21	-0.30	-0.43	-0.48	-0.38	-0.08	0.33	0.74	1.08	1.30
	+10	-0.23	0.10	0.31	0.32	0.14	-0.18	-0.51	-0.70	-0.64	-0.30	0.23	0.80	1.29
ELEVATION	0	-0.03	0.43	0.70	0.72	0.48	0.05	-0.49	-0.99	-1.30	-1.32	-1.02	-0.50	0.07
	-10	0.09	0.57	0.84	0.86	0.63	0.17	-0.44	-1.11	-1.74	-2.20	-2.39	-2.30	-2.02
	-20	-0.18	0.66	0.92	0.94	0.72	0.27	-0.40	-1.24	-2.18	-3.13	-3.98	-4.63	-5.03
	-30	0.34	0.89	1.17	1.19	0.95	0.44	-0.35	-1.42	-2.76	-4.29	-5.92	-7.50	-8.87

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-1.88	-2.09	-2.24	-2.25	-2.12	-1.91	-1.75	-1.76	-1.99	-2.36	-2.76	-3.12	-3.39
	+20	-1.99	-2.29	-2.49	-2.50	-2.33	-2.04	-1.75	-1.60	-1.71	-2.05	-2.50	-2.94	-3.28
	+10	-2.08	-2.46	-2.69	-2.71	-2.51	-2.15	-1.72	-1.37	-1.26	-1.47	-1.90	-2.41	-2.85
ELEVATION	0	-2.20	-2.64	-2.89	-2.91	-2.69	-2.28	-1.75	-1.24	-0.89	-0.84	-1.11	-1.60	-2.14
	-10	-2.26	-2.74	-3.01	-3.03	-2.79	-2.35	-1.76	-1.15	-0.62	-0.33	-0.35	-0.66	-1.12
	-20	-1.60	-2.11	-2.39	-2.41	-2.17	-1.69	-1.06	-0.35	0.32	0.81	1.05	0.97	0.65
	-30	-0.16	-0.68	-0.97	-1.00	-0.74	-0.25	0.42	1.19	1.95	2.59	3.01	3.15	3.03

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	2.11	1.45	0.56	-0.41	-1.32	-2.03	-2.41	-2.42	-2.13	-1.70	-1.26	-0.88	-0.58
	+20	2.18	1.42	0.54	-0.39	-1.29	-2.07	-2.62	-2.84	-2.69	-2.26	-1.73	-1.22	-0.80
	+10	2.09	1.32	0.49	-0.36	-1.19	-1.97	-2.64	-3.09	-3.22	-2.97	-2.44	-1.80	-1.21
ELEVATION	0	1.87	1.15	0.42	-0.31	-1.04	-1.76	-2.44	-3.03	-3.43	-3.51	-3.21	-2.60	-1.85
	-10	1.60	0.97	0.35	-0.26	-0.88	-1.50	-2.14	-2.76	-3.29	-3.63	-3.66	-3.30	-2.57
	-20	1.42	0.85	0.31	-0.22	-0.76	-1.33	-1.93	-2.56	-3.17	-3.68	-3.97	-3.89	-3.32
	-30	1.26	0.74	0.27	-0.20	-0.67	-1.18	-1.73	-2.33	-2.94	-3.49	-3.88	-3.94	-3.51

TABLE 3

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD - 0.15 m UP 0.0 FORWARD 0.0

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	2.43	1.81	1.12	0.40	-0.34	-1.07	-1.75	-2.38	-2.90	-3.28	-3.45	-3.36	-3.00
	+20	2.44	1.86	1.17	0.42	-0.36	-1.11	-1.80	-2.40	-2.88	-3.21	-3.37	-3.29	-2.94
	+10	2.37	1.85	1.19	0.43	-0.37	-1.13	-1.80	-2.33	-2.72	-2.97	-3.06	-2.97	-2.66
ELEVATION	0	2.30	1.85	1.21	0.44	-0.38	-1.15	-1.80	-2.27	-2.55	-2.68	-2.67	-2.53	-2.23
	-10	2.21	1.82	1.21	0.45	-0.38	-1.15	-1.78	-2.18	-2.37	-2.37	-2.24	-2.01	-1.71
	-20	1.54	1.34	0.92	0.35	-0.29	-0.88	-1.31	-1.53	-1.54	-1.38	-1.13	-0.85	-0.60
	-30	0.23	0.35	0.30	0.12	-0.10	-0.29	-0.35	-0.24	0.02	0.38	0.75	1.02	1.12

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	0.46	0.36	0.31	0.29	0.29	0.31	0.36	0.45	0.58	0.71	0.82	0.87	0.88
	+20	0.39	0.38	0.41	0.45	0.45	0.41	0.38	0.39	0.48	0.66	0.89	1.14	1.34
	+10	0.21	0.35	0.51	0.62	0.62	0.53	0.37	0.21	0.15	0.22	0.44	0.77	1.12
ELEVATION	0	-0.01	0.30	0.57	0.73	0.73	0.59	0.33	0.02	-0.26	-0.43	-0.42	-0.25	0.05
	-10	-0.15	0.25	0.57	0.74	0.75	0.59	0.28	-0.12	-0.55	-0.95	-1.24	-1.38	-1.36
	-20	-0.27	0.22	0.57	0.75	0.76	0.59	0.25	-0.23	-0.82	-1.47	-2.11	-2.68	-3.12
	-30	-0.44	0.20	0.63	0.84	0.85	0.65	0.24	-0.38	-1.19	-2.17	-3.26	-4.38	-5.44

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-2.42	-2.46	-2.54	-2.60	-2.60	-2.54	-2.46	-2.42	-2.46	-2.59	-2.80	-3.04	-3.26
	+20	-2.39	-2.51	-2.64	-2.73	-2.74	-2.65	-2.52	-2.39	-2.35	-2.43	-2.62	-2.88	-3.14
	+10	-2.27	-2.48	-2.68	-2.81	-2.81	-2.70	-2.50	-2.28	-2.12	-2.09	-2.21	-2.45	-2.73
ELEVATION	0	-2.18	-2.48	-2.74	-2.89	-2.89	-2.76	-2.51	-2.21	-1.92	-1.75	-1.73	-1.87	-2.15
	-10	-2.08	-2.45	-2.75	-2.91	-2.92	-2.76	-2.48	-2.12	-1.74	-1.44	-1.27	-1.27	-1.42
	-20	-1.31	-1.74	-2.06	-2.24	-2.25	-2.08	-1.77	-1.35	-0.90	-0.48	-0.18	-0.03	-0.05
	-30	0.21	-0.25	-0.60	-0.79	-0.80	-0.62	-0.28	0.17	0.68	1.18	1.59	1.87	1.98

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	1.55	1.31	0.89	0.33	-0.28	-0.85	-1.29	-1.54	-1.58	-1.46	-1.23	-0.97	-0.72
	+20	1.78	1.44	0.95	0.34	-0.29	-0.90	-1.41	-1.76	-1.90	-1.83	-1.61	-1.30	-0.97
	+10	1.91	1.48	0.94	0.34	-0.29	-0.89	-1.44	-1.88	-2.15	-2.22	-2.07	-1.76	-1.37
ELEVATION	0	1.86	1.39	0.86	0.31	-0.26	-0.82	-1.35	-1.83	-2.21	-2.42	-2.44	-2.24	-1.85
	-10	1.70	1.24	0.76	0.27	-0.23	-0.72	-1.20	-1.66	-2.08	-2.39	-2.56	-2.51	-2.23
	-20	1.59	1.14	0.68	0.24	-0.20	-0.65	-1.10	-1.55	-1.99	-2.37	-2.64	-2.73	-2.57
	-30	1.47	1.04	0.62	0.22	-0.18	-0.58	-1.00	-1.43	-1.86	-2.26	-2.57	-2.73	-2.65

TABLE 4

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.0 UP 0.15 m FORWARD 0.0

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	2.56	1.77	0.91	0.00	-0.91	-1.77	-2.56	-3.23	-3.74	-4.04	-4.06	-3.77	-3.16
	+20	2.67	1.88	0.98	0.00	-0.98	-1.88	-2.67	-3.31	-3.77	-4.03	-4.04	-3.75	-3.15
	+10	2.69	1.93	1.01	0.00	-1.01	-1.93	-2.69	-3.25	-3.62	-3.80	-3.78	-3.50	-2.94
ELEVATION	0	2.68	1.96	1.04	0.00	-1.04	-1.96	-2.68	-3.15	-3.40	-3.46	-3.36	-3.07	-2.57
	-10	2.60	1.94	1.04	0.00	-1.04	-1.94	-2.60	-2.99	-3.11	-3.04	-2.82	-2.49	-2.05
	-20	1.95	1.50	0.82	0.00	-0.82	-1.50	-1.95	-2.12	-2.05	-1.82	-1.51	-1.20	-0.90
	-30	0.62	0.58	0.35	-0.00	-0.35	-0.58	-0.62	-0.44	-0.10	0.32	0.70	0.93	0.96

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	0.67	0.71	0.76	0.78	0.76	0.71	0.67	0.64	0.63	0.61	0.56	0.48	0.37
	+20	0.84	0.96	1.08	1.12	1.08	0.96	0.84	0.75	0.76	0.84	0.96	1.08	1.17
	+10	0.88	1.11	1.29	1.36	1.29	1.11	0.88	0.69	0.61	0.69	0.89	1.16	1.43
ELEVATION	0	0.74	1.06	1.28	1.36	1.28	1.06	0.74	0.43	0.21	0.14	0.26	0.52	0.85
	-10	0.52	0.85	1.08	1.15	1.08	0.85	0.52	0.14	-0.22	-0.48	-0.58	-0.51	-0.32
	-20	0.47	0.83	1.05	1.13	1.05	0.83	0.47	-0.00	-0.54	-1.07	-1.53	-1.87	-2.06
	-30	0.57	1.03	1.31	1.40	1.31	1.03	0.57	-0.09	-0.92	-1.88	-2.89	-3.88	-4.73

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-2.59	-2.70	-2.81	-2.85	-2.81	-2.70	-2.59	-2.54	-2.61	-2.78	-3.02	-3.26	-3.48
	+20	-2.69	-2.87	-3.02	-3.08	-3.02	-2.87	-2.69	-2.56	-2.55	-2.68	-2.91	-3.18	-3.43
	+10	-2.69	-2.95	-3.14	-3.21	-3.14	-2.95	-2.69	-2.46	-2.33	-2.37	-2.56	-2.84	-3.13
ELEVATION	0	-2.67	-3.00	-3.23	-3.31	-3.23	-3.00	-2.68	-2.34	-2.08	-1.98	-2.07	-2.31	-2.61
	-10	-2.60	-2.97	-3.23	-3.32	-3.23	-2.97	-2.60	-2.18	-1.80	-1.57	-1.52	-1.65	-1.90
	-20	-1.82	-2.25	-2.53	-2.63	-2.53	-2.25	-1.82	-1.32	-0.85	-0.48	-0.28	-0.28	-0.45
	-30	-0.28	-0.74	-1.05	-1.15	-1.05	-0.74	-0.28	0.28	0.85	1.34	1.60	1.84	1.80

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	1.42	1.08	0.58	0.00	-0.58	-1.08	-1.42	-1.56	-1.50	-1.31	-1.06	-0.80	-0.56
	+20	1.53	1.13	0.59	-0.00	-0.59	-1.13	-1.53	-1.75	-1.77	-1.61	-1.34	-1.03	-0.73
	+10	1.57	1.11	0.58	0.00	-0.58	-1.11	-1.57	-1.89	-2.03	-1.97	-1.72	-1.38	-1.00
ELEVATION	0	1.50	1.04	0.53	0.00	-0.53	-1.04	-1.50	-1.89	-2.16	-2.24	-2.11	-1.80	-1.38
	-10	1.37	0.92	0.46	0.00	-0.46	-0.92	-1.37	-1.78	-2.13	-2.34	-2.37	-2.18	-1.78
	-20	1.28	0.84	0.42	0.00	-0.42	-0.84	-1.28	-1.72	-2.13	-2.47	-2.65	-2.60	-2.28
	-30	1.20	0.78	0.38	0.00	-0.38	-0.78	-1.20	-1.65	-2.09	-2.43	-2.79	-2.86	-2.63

TABLE 5

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.0 UP - 0.15 m FORWARD 0.0

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	1.86	1.24	0.62	0.00	-0.62	-1.24	-1.86	-2.48	-3.04	-3.44	-3.59	-3.42	-2.92
	+20	1.84	1.28	0.66	-0.00	-0.66	-1.28	-1.84	-2.36	-2.82	-3.18	-3.35	-3.23	-2.79
	+10	1.81	1.32	0.70	0.00	-0.70	-1.32	-1.81	-2.18	-2.46	-2.67	-2.79	-2.72	-2.38
	0	1.86	1.41	0.76	0.00	-0.76	-1.41	-1.86	-2.10	-2.18	-2.17	-2.11	-1.99	-1.74
	-10	1.90	1.47	0.81	0.00	-0.81	-1.47	-1.90	-2.05	-1.98	-1.76	-1.50	-1.25	-1.01
	-20	1.33	1.10	0.62	-0.00	-0.62	-1.10	-1.33	-1.29	-1.02	-0.62	-0.20	0.11	0.27
	-30	0.11	0.25	0.19	0.00	-0.19	-0.25	-0.11	0.25	0.78	1.36	1.85	2.11	2.04

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	-1.16	-1.47	-1.64	-1.69	-1.64	-1.47	-1.16	-0.72	-0.21	0.26	0.63	0.86	0.97
	+20	-1.50	-1.55	-1.52	-1.50	-1.52	-1.55	-1.50	-1.28	-0.85	-0.27	0.34	0.88	1.29
	+10	-1.57	-1.30	-1.07	-0.99	-1.07	-1.30	-1.57	-1.76	-1.72	-1.39	-0.80	-0.11	0.54
	0	-1.35	-0.84	-0.49	-0.36	-0.49	-0.84	-1.35	-1.90	-2.34	-2.56	-2.45	-2.05	-1.49
	-10	-0.98	-0.39	0.00	0.13	0.00	-0.39	-0.98	-1.71	-2.48	-3.18	-3.68	-3.93	-3.92
	-20	-0.82	-0.17	0.23	0.37	0.23	-0.17	-0.82	-1.68	-2.71	-3.83	-4.93	-5.93	-6.72
	-30	-0.79	-0.05	0.39	0.53	0.39	-0.05	-0.79	-1.82	-3.13	4.67	-6.37	-8.09	-9.69

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	-1.59	-1.72	-1.87	-1.93	-1.87	-1.72	-1.59	-1.58	-1.77	-2.10	-2.50	-2.87	-3.16
	+20	-1.52	-1.78	-1.99	-2.08	-1.99	-1.78	-1.52	-1.35	-1.39	-1.67	-2.10	-2.56	-2.94
	+10	-1.49	-1.86	-2.13	-2.23	-2.13	-1.86	-1.49	-1.12	-0.92	-1.00	-1.35	-1.85	-2.34
	0	-1.58	-2.02	-2.33	-2.44	-2.33	-2.02	-1.58	-1.08	-0.66	-0.45	-0.54	-0.91	-1.40
	-10	-1.67	-2.15	-2.47	-2.59	-2.48	-2.15	-1.67	-1.11	-0.56	-0.15	0.02	-0.08	-0.40
	-20	-1.04	-1.56	-1.90	-2.01	-1.90	-1.56	-1.04	-0.42	0.21	0.76	1.14	1.25	1.16
	-30	0.35	-0.18	-0.53	-0.65	-0.53	-0.18	0.35	0.99	1.69	2.32	2.81	3.10	3.17

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
ELEVATION	+30	2.44	1.89	1.02	-0.00	-1.02	-1.89	-2.44	-2.59	-2.40	-1.98	-1.52	-1.10	-0.75
	+20	2.69	1.96	1.02	-0.00	-1.02	-1.96	-2.69	-3.10	3.11	-2.75	-2.19	-1.60	-1.10
	+10	2.65	1.83	0.93	0.00	-0.93	-1.83	-2.65	-3.29	-3.64	-3.59	-3.14	-2.45	-1.73
	0	2.35	1.58	0.79	0.00	-0.79	-1.58	-2.35	-3.07	-3.65	-3.97	-3.91	-3.43	-2.65
	-10	1.99	1.32	0.66	0.00	-0.66	-1.32	-1.99	-2.66	-3.27	-3.77	-4.01	-3.89	-3.34
	-20	1.74	1.14	0.56	0.00	-0.56	-1.14	-1.74	-2.36	-2.98	-3.53	-3.92	-4.01	-3.68
	-30	1.52	0.99	0.48	0.00	-0.48	-0.99	-1.52	-2.01	-2.63	-3.14	-3.52	-3.66	-3.41

TABLE 6

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.0 UP 0.0 FORWARD 0.15 m

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	2.69	1.94	1.16	0.35	-0.47	-1.28	-2.06	-2.80	-3.47	-4.00	-4.27	-4.21	-3.76
	+20	2.75	2.06	1.27	0.39	-0.53	-1.40	-2.17	-2.84	-3.41	-3.86	-4.12	-4.07	-3.66
	+10	2.73	2.14	1.35	0.42	-0.57	-1.48	-2.24	-2.81	-3.21	-3.49	-3.65	-3.61	-3.28
ELEVATION	0	2.74	2.23	1.44	0.45	-0.61	-1.58	-2.32	-2.80	-3.03	-3.09	-3.05	-2.93	-2.64
	-10	2.71	2.26	1.49	0.47	-0.63	-1.63	-2.36	-2.75	-2.83	-2.69	-2.43	-2.14	-1.83
	-20	1.94	1.72	1.17	0.37	-0.51	-1.27	-1.78	-1.94	-1.78	-1.40	-0.94	-0.53	-0.25
	-30	0.33	0.53	0.45	0.15	-0.21	-0.48	-0.52	-0.28	0.22	0.87	1.50	1.95	2.07

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-0.43	-0.59	-0.66	-0.68	-0.68	-0.66	-0.58	-0.40	-0.12	0.17	0.41	0.54	0.56
	+20	-0.48	-0.43	-0.30	-0.21	-0.22	-0.32	-0.44	-0.48	-0.34	-0.02	0.40	0.80	1.12
	+10	-0.51	-0.18	0.14	0.32	0.31	0.10	-0.23	-0.55	-0.71	-0.60	-0.22	0.32	0.89
ELEVATION	0	-0.49	0.05	0.48	0.72	0.70	0.43	-0.03	-0.57	-1.05	-1.33	-1.29	-0.95	0.41
	-10	-0.44	0.17	0.63	0.86	0.84	0.57	0.09	-0.54	-1.22	-1.83	-2.25	-2.40	-2.27
	-20	-0.40	0.27	0.72	0.94	0.92	0.66	0.18	-0.52	-1.38	-2.33	-3.27	-4.10	-4.71
	-30	-0.35	0.44	0.95	1.19	1.17	0.89	0.34	-0.50	-1.61	-2.98	-4.54	-6.17	-7.73

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-1.75	-1.91	-2.12	-2.25	-2.24	-2.09	-1.88	-1.74	-1.78	-2.04	-2.42	-2.82	-3.17
	+20	-1.75	-2.04	-2.33	-2.50	-2.49	-2.29	-1.99	-1.71	-1.60	-1.75	-2.12	-2.57	-3.00
	+10	-1.72	-2.15	-2.51	-2.71	-2.69	-2.46	-2.08	-1.66	-1.34	-1.27	-1.52	-1.98	-2.49
ELEVATION	0	-1.75	-2.28	-2.69	-2.91	-2.89	-2.64	-2.20	-1.67	-1.17	-0.86	-0.86	-1.18	-1.68
	-10	-1.76	-2.35	-2.79	-3.03	-3.01	-2.74	-2.26	-1.67	-1.06	-0.56	-0.31	-0.38	-0.72
	-20	-1.06	-1.69	-2.17	-2.41	-2.39	-2.11	-1.60	-0.95	-0.24	0.41	0.87	1.06	0.94
	-30	0.42	-0.25	-0.74	-1.00	-0.97	-0.68	-0.16	0.54	1.31	2.06	2.68	3.05	3.15

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	2.41	2.03	1.32	0.41	-0.56	-1.45	-2.11	-2.43	-2.39	-2.07	-1.63	-1.20	-0.83
	+20	2.62	2.07	1.29	0.39	-0.54	-1.42	-2.18	-2.68	-2.84	-2.64	-2.18	-1.65	-1.15
	+10	2.64	1.97	1.19	0.36	-0.49	-1.32	-2.09	-2.73	-3.14	-3.20	-2.90	-2.34	-1.71
ELEVATION	0	2.44	1.76	1.04	0.31	-0.42	-1.15	-1.87	-2.54	-3.11	-3.47	-3.49	-3.13	-2.49
	-10	2.14	1.50	0.88	0.26	-0.35	-0.97	-1.60	-2.24	-2.85	-3.36	-3.66	-3.63	-3.20
	-20	1.93	1.33	0.76	0.22	-0.31	-0.85	-1.42	-2.03	-2.66	-3.26	-3.75	-3.99	-3.83
	-30	1.73	1.18	0.67	0.20	-0.27	-0.74	-1.26	-1.82	-2.44	-3.03	-3.57	-3.91	-3.91

TABLE 7

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.0 UP 0.0 FORWARD - 0.15 m

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	1.75	1.07	0.34	-0.40	-1.12	-1.81	-2.43	-2.94	-3.30	-3.45	-3.34	-2.96	-2.31
	+20	1.80	1.11	0.36	-0.42	-1.17	-1.86	-2.44	-2.91	-3.24	-3.37	-3.27	-2.90	-2.27
	+10	1.80	1.13	0.37	-0.43	-1.19	-1.85	-2.37	-2.75	-2.98	-3.06	-2.96	-2.63	-2.07
ELEVATION	0	1.80	1.15	0.38	-0.44	-1.21	-1.85	-2.30	-2.57	-2.68	-2.66	-2.51	-2.20	-1.73
	-10	1.78	1.15	0.38	-0.45	-1.21	-1.82	-2.21	-2.38	-2.37	-2.22	-1.99	-1.68	-1.28
	-20	1.31	0.88	0.29	-0.35	-0.92	-1.34	-1.54	-1.54	-1.36	-1.11	-0.83	-0.58	-0.38
	-30	0.35	0.29	0.10	-0.12	-0.30	-0.35	-0.23	0.05	0.41	0.77	1.03	1.12	0.99

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	0.36	0.31	0.29	0.29	0.31	0.36	0.46	0.59	0.72	0.82	0.87	0.87	0.84
	+20	0.38	0.41	0.45	0.45	0.41	0.38	0.39	0.49	0.68	0.91	1.16	1.36	1.50
	+10	0.37	0.53	0.62	0.62	0.51	0.35	0.21	0.15	0.24	0.47	0.79	1.14	1.45
ELEVATION	0	0.33	0.59	0.73	0.73	0.57	0.30	-0.01	-0.28	-0.44	-0.42	-0.23	0.08	0.40
	-10	0.28	0.59	0.75	0.74	0.57	0.25	-0.15	-0.59	-0.98	-1.26	-1.38	-1.35	-1.22
	-20	0.25	0.59	0.76	0.75	0.57	0.22	-0.27	-0.87	-1.52	-2.16	-2.72	-3.16	-3.44
	-30	0.24	0.65	0.85	0.84	0.63	0.20	-0.44	-1.27	-2.26	-3.36	-4.48	-5.53	-6.41

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-2.46	-2.54	-2.60	-2.60	-2.54	-2.46	-2.42	-2.46	-2.61	-2.82	-3.06	-3.28	-3.45
	+20	-2.52	-2.65	-2.74	-2.73	-2.64	-2.51	-2.39	-2.35	-2.44	-2.64	-2.90	-3.16	-3.37
	+10	-2.50	-2.70	-2.81	-2.81	-2.68	-2.48	-2.27	-2.11	-2.09	-2.23	-2.47	-2.75	-3.01
ELEVATION	0	-2.51	-2.76	-2.89	-2.89	-2.74	-2.48	-2.18	-1.90	-1.74	-1.73	-1.89	-2.15	-2.42
	-10	-2.48	-2.76	-2.92	-2.91	-2.75	-2.45	-2.08	-1.71	-1.42	-1.27	-1.28	-1.44	-1.67
	-20	-1.77	-2.08	-2.25	-2.24	-2.06	-1.73	-1.31	-0.86	-0.45	-0.16	-0.03	-0.06	-0.21
	-30	-0.28	-0.62	-0.80	-0.79	-0.60	-0.25	0.21	0.73	1.22	1.62	1.88	1.98	1.94

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	1.29	0.85	0.28	-0.33	-0.89	-1.31	-1.55	-1.58	-1.44	-1.21	-0.95	-0.70	-0.47
	+20	1.41	0.90	0.29	-0.34	-0.95	-1.44	-1.78	-1.90	1.82	-1.58	-1.27	-0.94	-0.64
	+10	1.44	0.89	0.28	-0.34	-0.94	-1.48	-1.91	-2.17	-2.21	-2.05	-1.73	-1.33	-0.92
ELEVATION	0	1.35	0.82	0.26	-0.31	-0.86	-1.39	-1.86	-2.23	-2.43	-2.43	-2.21	-1.81	-1.32
	-10	1.20	0.72	0.23	-0.27	-0.76	-1.24	-1.70	-2.11	-2.41	-2.56	-2.50	-2.20	-1.69
	-20	1.10	0.65	0.20	-0.24	-0.68	-1.14	-1.59	-2.02	-2.40	-2.66	-2.73	-2.54	-2.07
	-30	1.00	0.58	0.18	-0.22	-0.62	-1.04	-1.47	-1.89	-2.30	-2.60	-2.74	-2.63	-2.21

TABLE 8

COLLIMATION PERFORMANCE DATA

PILOT OFFSETS: OUTBOARD 0.15 m UP - 0.15 m FORWARD 0.15 m

HORIZONTAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	1.77	1.14	0.56	0.00	-0.56	-1.14	-1.77	-2.51	-3.30	-3.97	-4.33	-4.23	-3.66
	+20	1.85	1.31	0.69	0.00	-0.69	-1.31	-1.85	-2.38	-2.95	-3.54	-3.94	-3.95	-3.48
	+10	1.96	1.50	0.82	-0.00	-0.82	-1.50	-1.96	-2.26	-2.49	-2.78	-3.08	-3.19	-2.92
ELEVATION	0	2.16	1.71	0.95	-0.00	-0.95	-1.71	-2.16	-2.30	-2.22	-2.10	-2.06	-2.08	-1.96
	-10	2.32	1.87	1.05	0.00	-1.05	-1.87	-2.32	-2.35	-2.06	-1.62	-1.20	-0.93	-0.78
	-20	1.68	1.46	0.84	0.00	-0.84	-1.46	-1.68	-1.48	-0.93	-0.20	0.50	0.96	1.10
	-30	0.20	0.42	0.31	-0.00	-0.31	-0.42	-0.20	0.40	1.27	2.24	3.07	3.54	3.46

VERTICAL DISTORTION PERCENT OF HEIGHT

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-2.95	-3.37	-3.56	-3.60	-3.56	-3.37	-2.95	-2.23	-1.33	-0.47	0.16	0.52	0.68
	+20	-3.01	-2.91	-2.73	-2.65	-2.73	-2.91	-3.01	-2.84	-2.24	-1.31	-0.31	0.52	1.10
	+10	-2.60	-2.04	-1.60	-1.44	-1.60	-2.04	-2.60	-3.07	-3.18	-2.75	-1.82	-0.69	0.31
ELEVATION	0	-1.92	-1.10	-0.55	-0.35	-0.55	-1.10	-1.92	-2.82	-3.61	-4.04	-3.90	-3.20	-2.21
	-10	-1.26	-0.40	0.15	0.34	0.15	-0.40	-1.26	-2.33	-3.48	-4.55	-5.34	-5.69	-5.57
	-20	-0.90	-0.04	0.48	0.65	0.48	-0.04	-0.90	-2.07	-3.50	-5.09	-6.72	-8.23	-9.44
	-30	-0.66	0.25	0.78	0.96	0.78	0.25	-0.66	-1.97	-3.69	-5.78	-8.15	-10.66	-13.07

CONVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	-0.48	-0.88	-1.25	-1.39	-1.25	-0.88	-0.48	-0.36	-0.67	-1.31	-2.01	-2.63	-3.08
	+20	-0.57	-1.15	-1.59	-1.75	-1.59	-1.15	-0.57	-0.11	-0.07	-0.58	-1.40	-2.19	-2.80
	+10	-0.78	-1.46	-1.93	-2.10	-1.93	-1.46	-0.78	-0.05	0.45	0.40	-0.25	-1.19	-2.04
ELEVATION	0	-1.08	-1.81	-2.29	-2.46	-2.29	-1.81	-1.08	-0.23	0.55	1.02	0.91	0.21	-0.75
	-10	-1.32	-2.06	-2.55	-2.72	-2.55	-2.06	-1.32	-0.44	0.46	1.19	1.54	1.37	0.73
	-20	-0.78	-1.54	-2.03	-2.21	-2.03	-1.54	-0.78	0.14	1.12	2.00	2.71	2.86	2.61
	-30	0.55	-0.20	-0.70	-0.87	-0.70	-0.20	0.55	1.49	2.49	3.43	4.18	4.60	4.66

DIPVERGENCE - MILLIRADIANS

AZIMUTH		90	75	60	45	30	15	0	15	30	45	60	75	90
	+30	4.08	3.13	1.67	-0.00	-1.67	-3.13	-4.08	-4.27	-3.74	-2.86	-2.01	-1.34	-0.87
	+20	4.06	2.87	1.47	-0.00	-1.47	-2.86	-4.06	-4.81	-4.81	-4.08	-3.01	-2.04	-1.30
	+10	3.64	2.44	1.22	0.00	-1.22	-2.44	-3.64	-4.70	-5.39	-5.37	-4.56	-3.34	-2.19
ELEVATION	0	3.04	2.00	0.99	0.00	-0.99	-2.00	-3.04	-4.10	-5.08	-5.77	-5.83	-5.06	-3.75
	-10	2.48	1.61	0.79	0.00	-0.79	-1.61	-2.48	-3.41	-4.37	-5.26	-5.88	-5.93	-5.17
	-20	2.11	1.36	0.66	0.00	-0.66	-1.36	-2.11	-2.95	-3.84	-4.75	-5.53	-5.98	-5.78
	-30	1.79	1.14	0.55	0.00	-0.55	-1.14	-1.79	-2.51	-3.29	-4.07	-4.76	-5.16	-5.02

COLLIMATING SYSTEM DISTORTION.

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD 0.0

UP 0.0

FORWARD 0.0

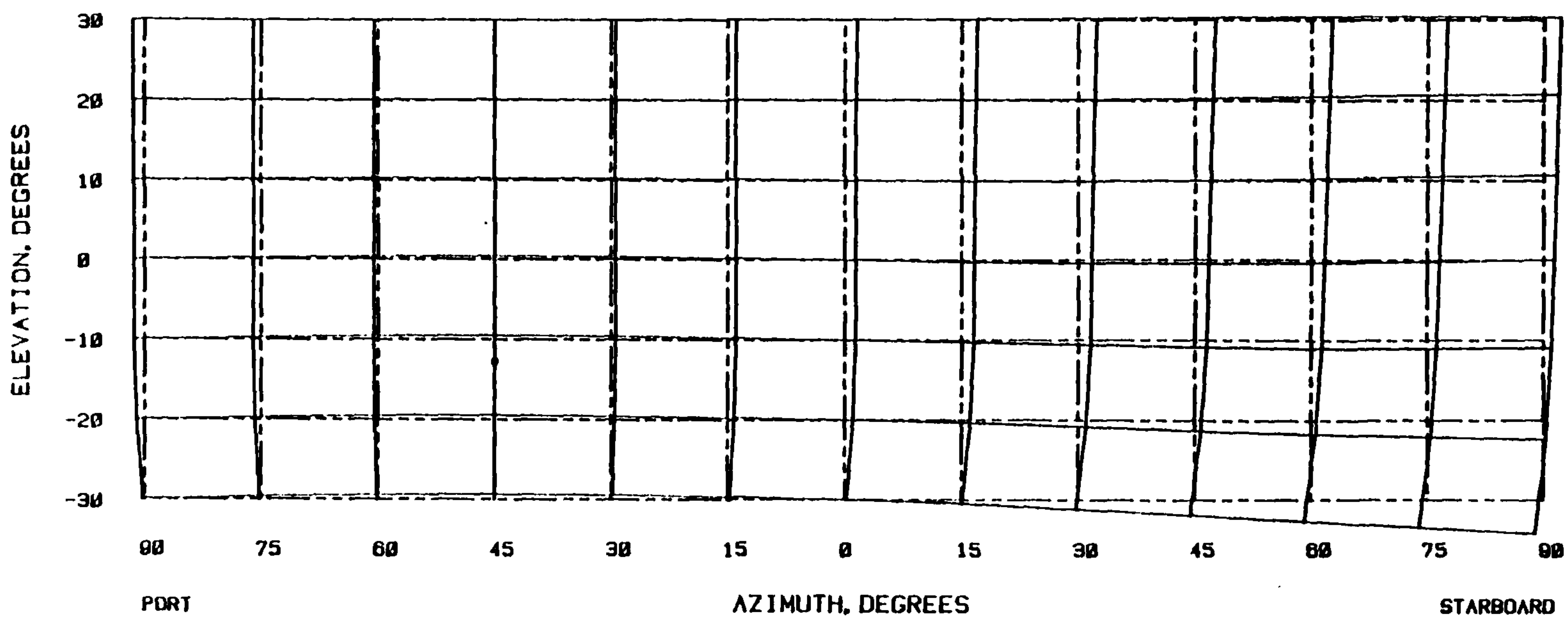


FIGURE 2

COLLIMATING SYSTEM DISTORTION,

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD 0.15 m

UP 0.0

FORWARD 0.0

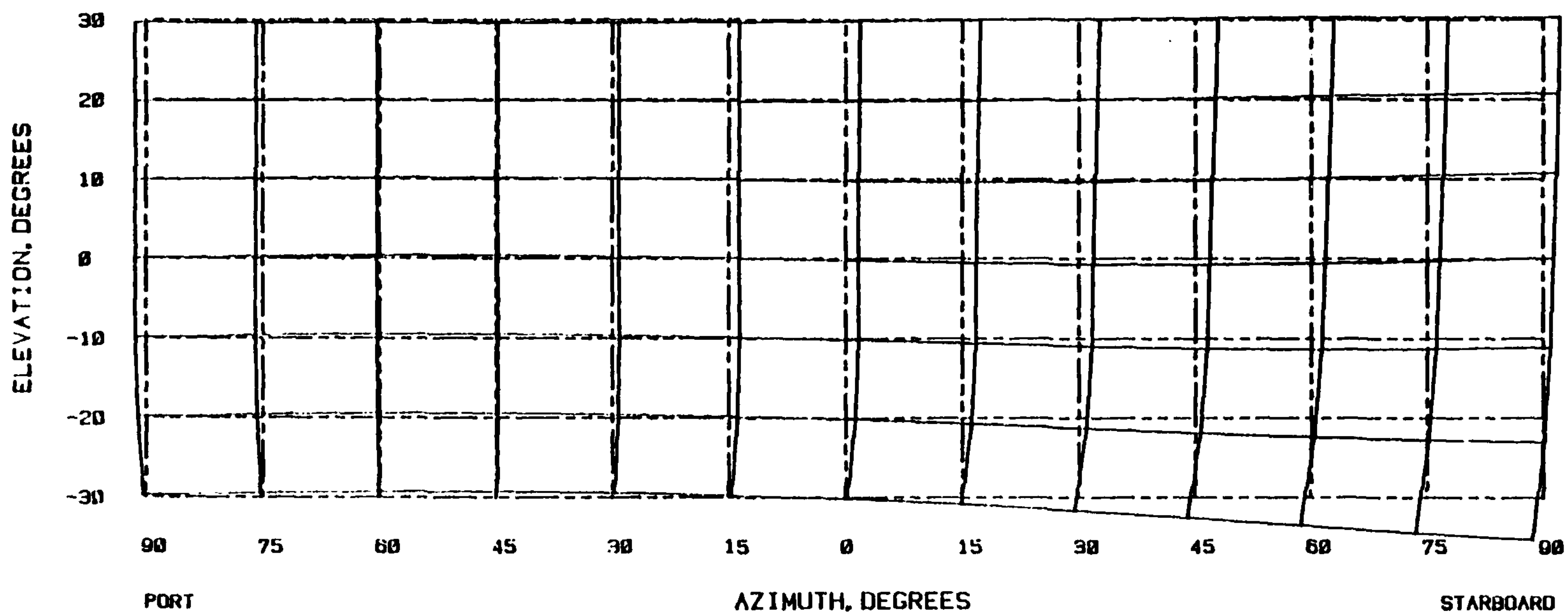


FIGURE 3

COLLIMATING SYSTEM DISTORTION,

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD-0.15 m

UP 0.0

FORWARD 0.0

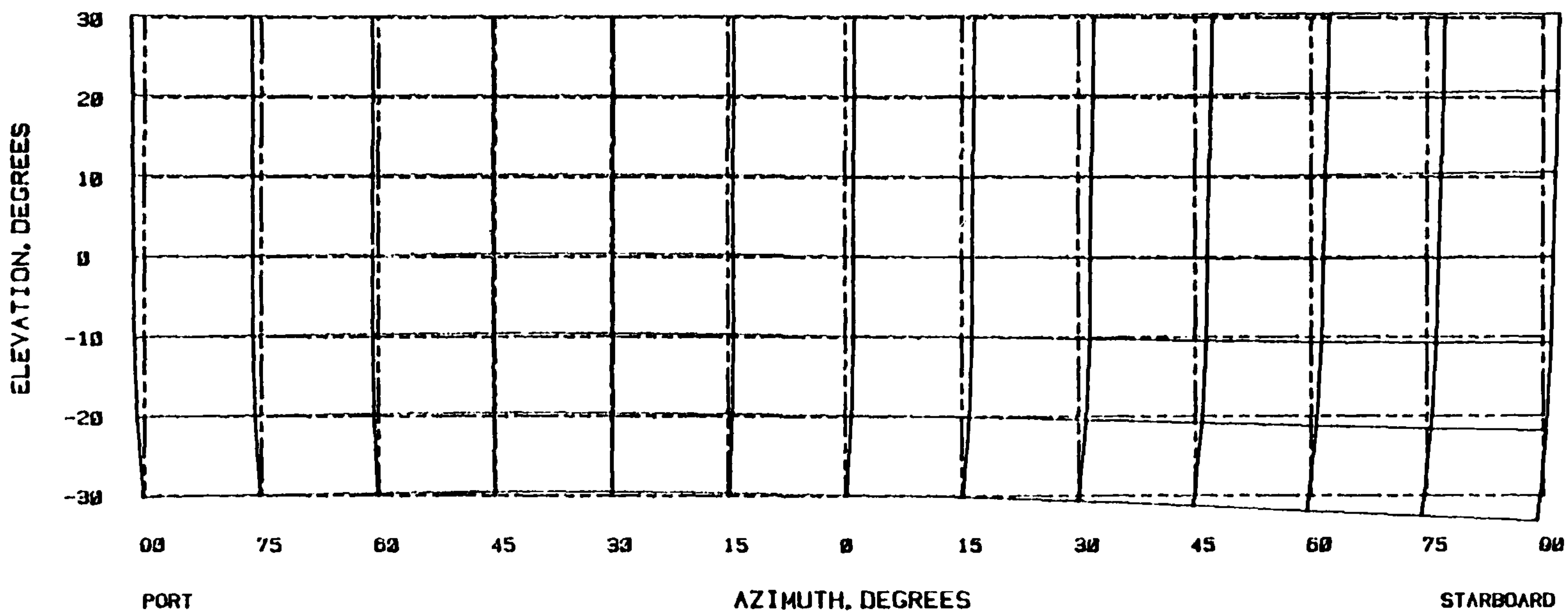


FIGURE 4

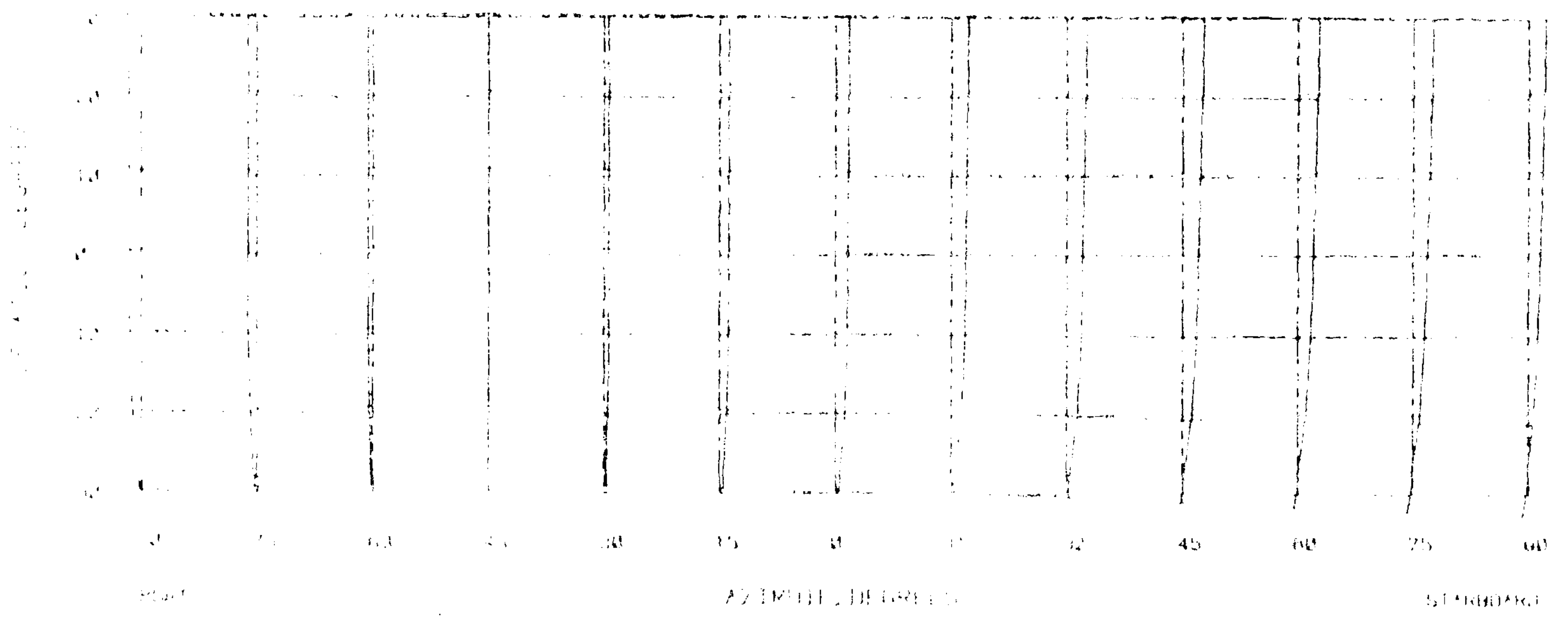
COLLIMATING SYSTEM DISTORTION,

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD 0.0

UP 0.75

FORWARD 0.0



COLLIMATING SYSTEM DISTORTION.

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD 0.0

UP-0.15 m

FORWARD 0.0

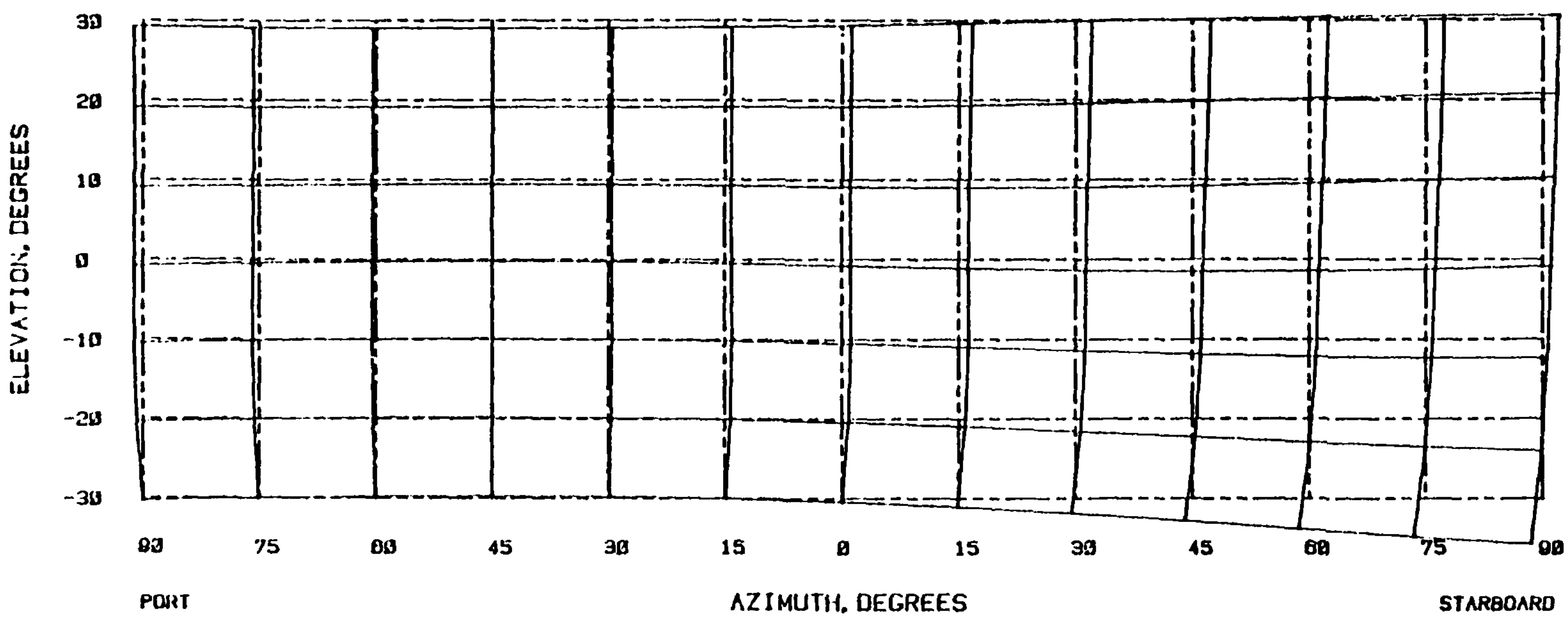


FIGURE 6

COLLIMATING SYSTEM DISTORTION.

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD 0.0

UP 0.0

FORWARD 0.15 m

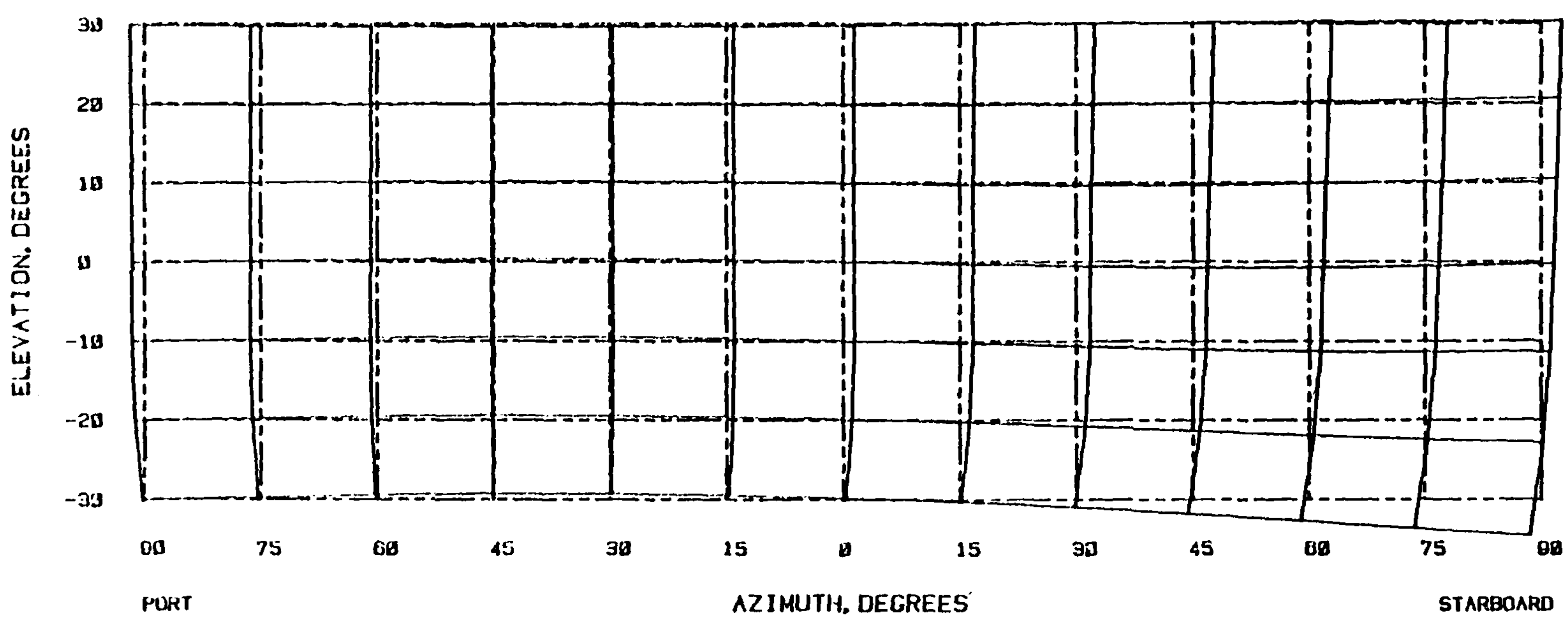


FIGURE 7

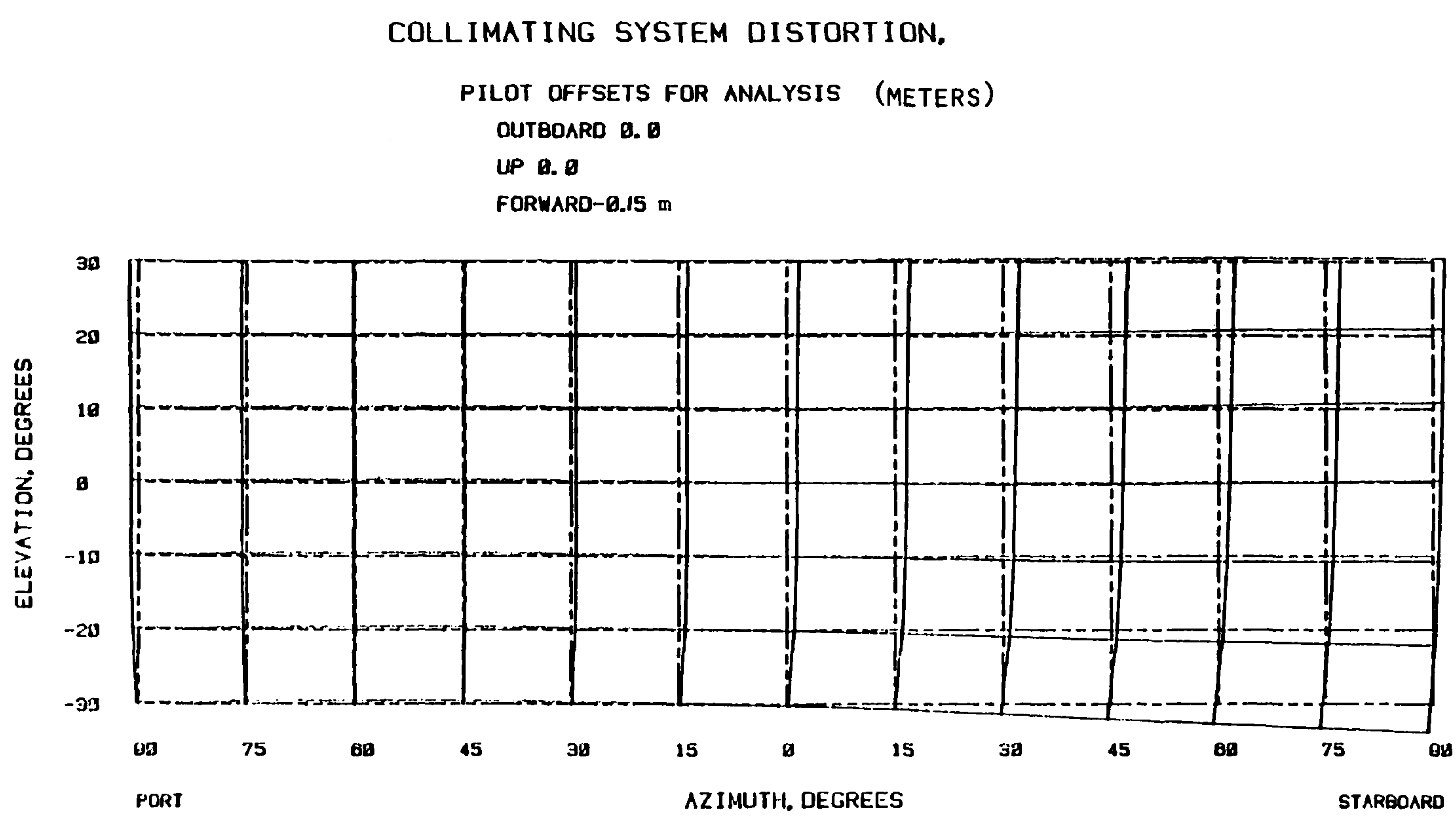

COLLIMATING SYSTEM DISTORTION,
PILOT OFFSETS FOR ANALYSIS (METERS)
OUTBOARD 0.0
UP 0.0
FORWARD-0.15 m
30
20
10
0
-10
-20
-30
ELEVATION, DEGREES
90
75
60
45
30
15
0
15
30
45
60
75
90
PORT
AZIMUTH, DEGREES
STARBOARD

FIGURE 8

COLLIMATING SYSTEM DISTORTION.

PILOT OFFSETS FOR ANALYSIS (METERS)

OUTBOARD Ø.15 m

UP-Ø.15 m

FORWARD Ø.15 m

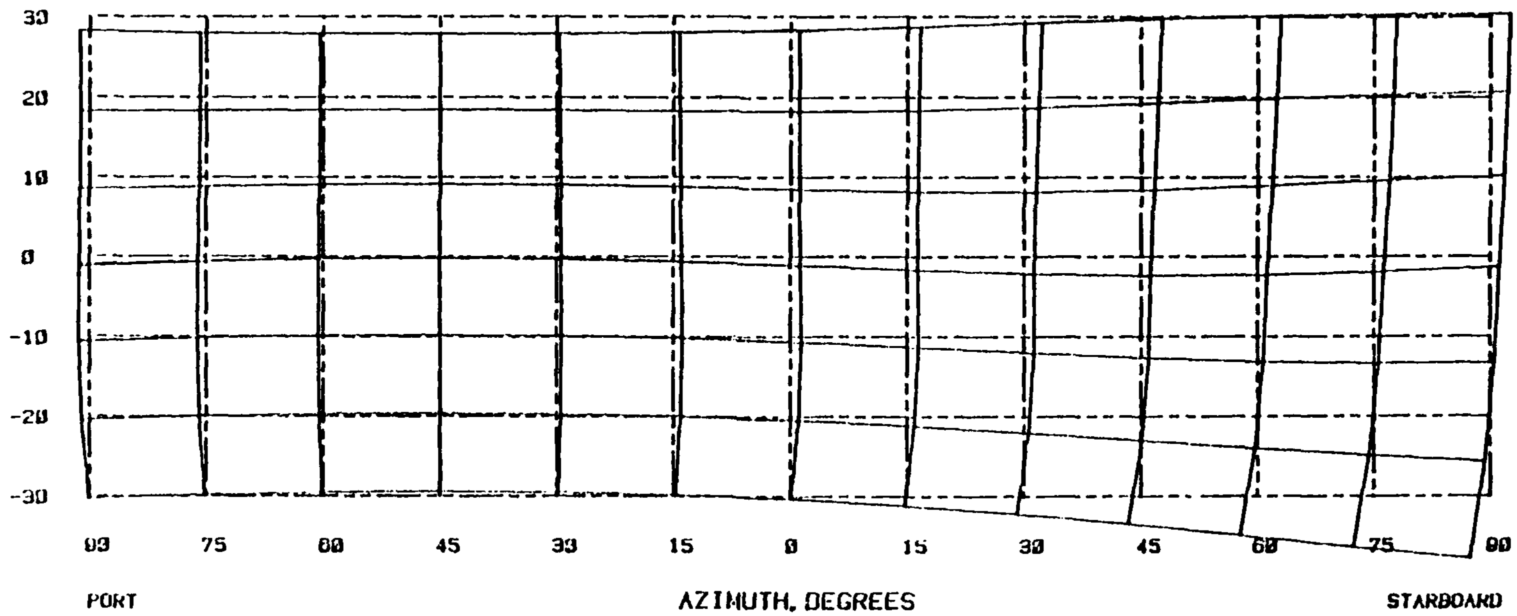


FIGURE 9

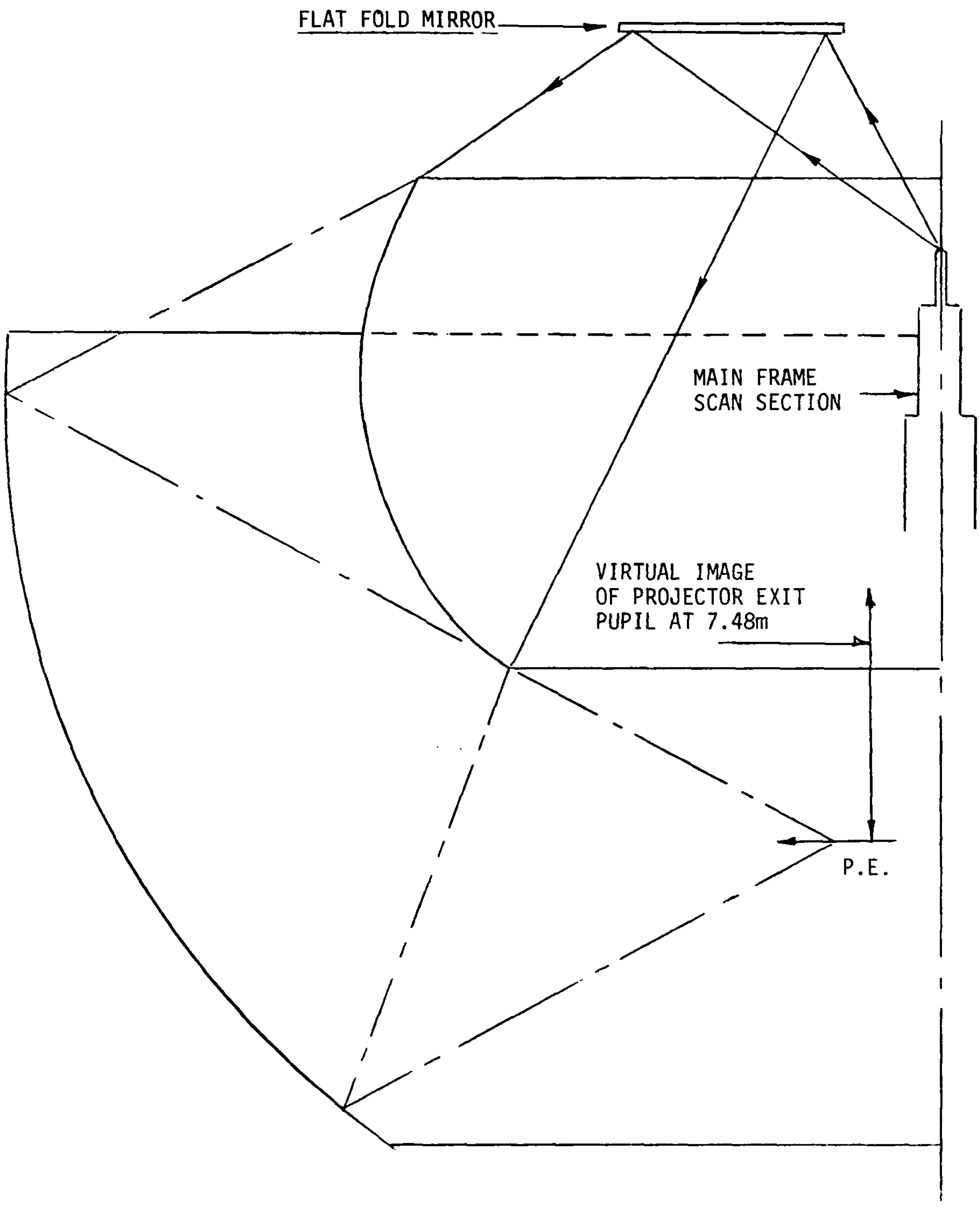


FIGURE 10. LASER PROJECTOR SYSTEM

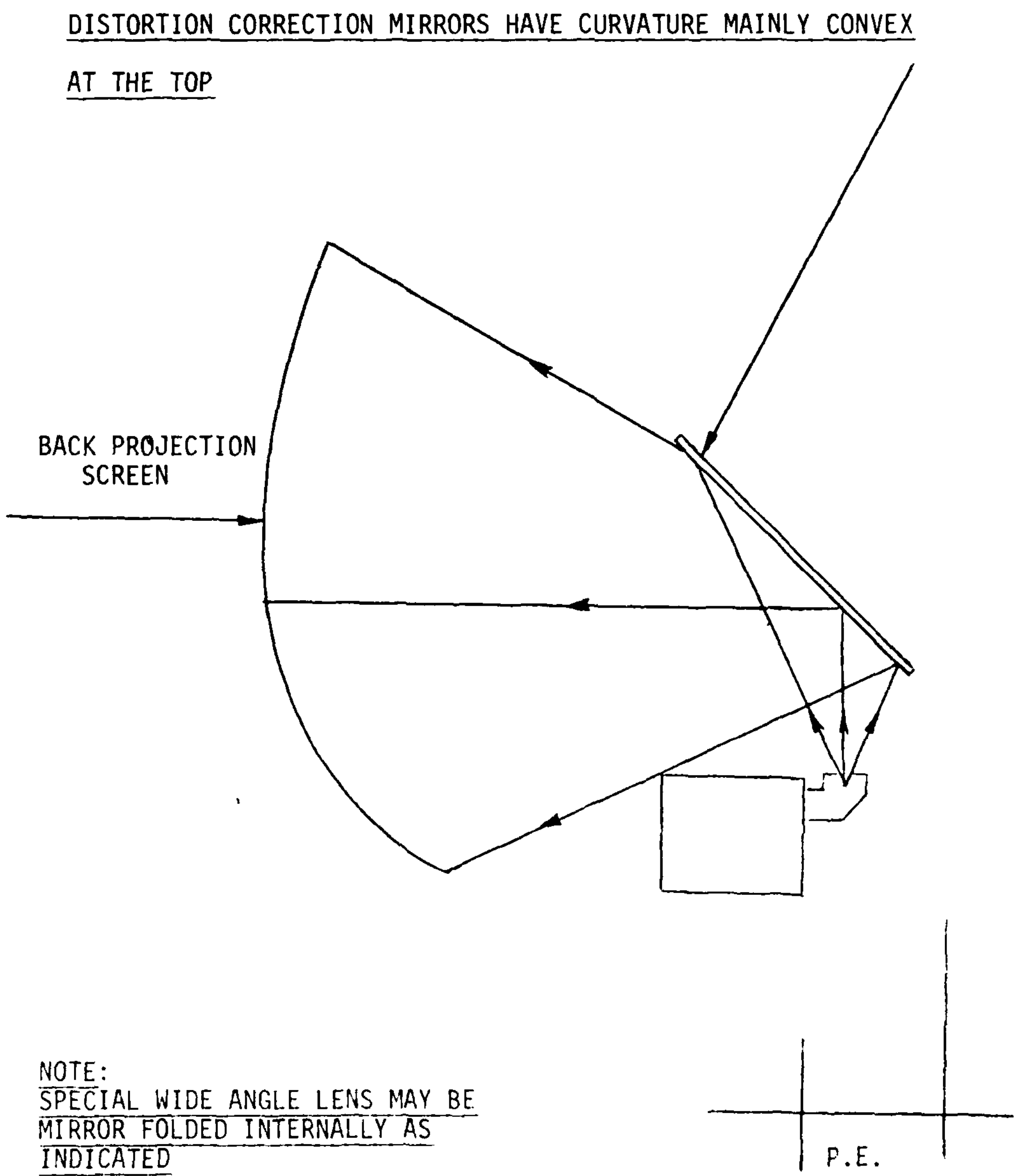


FIGURE 11. PROJECTION SYSTEM USING 3 OIL FILM LIGHT VALVE PROJECTORS WITH NEARLY FLAT DISTORTION-CORRECTION MIRRORS

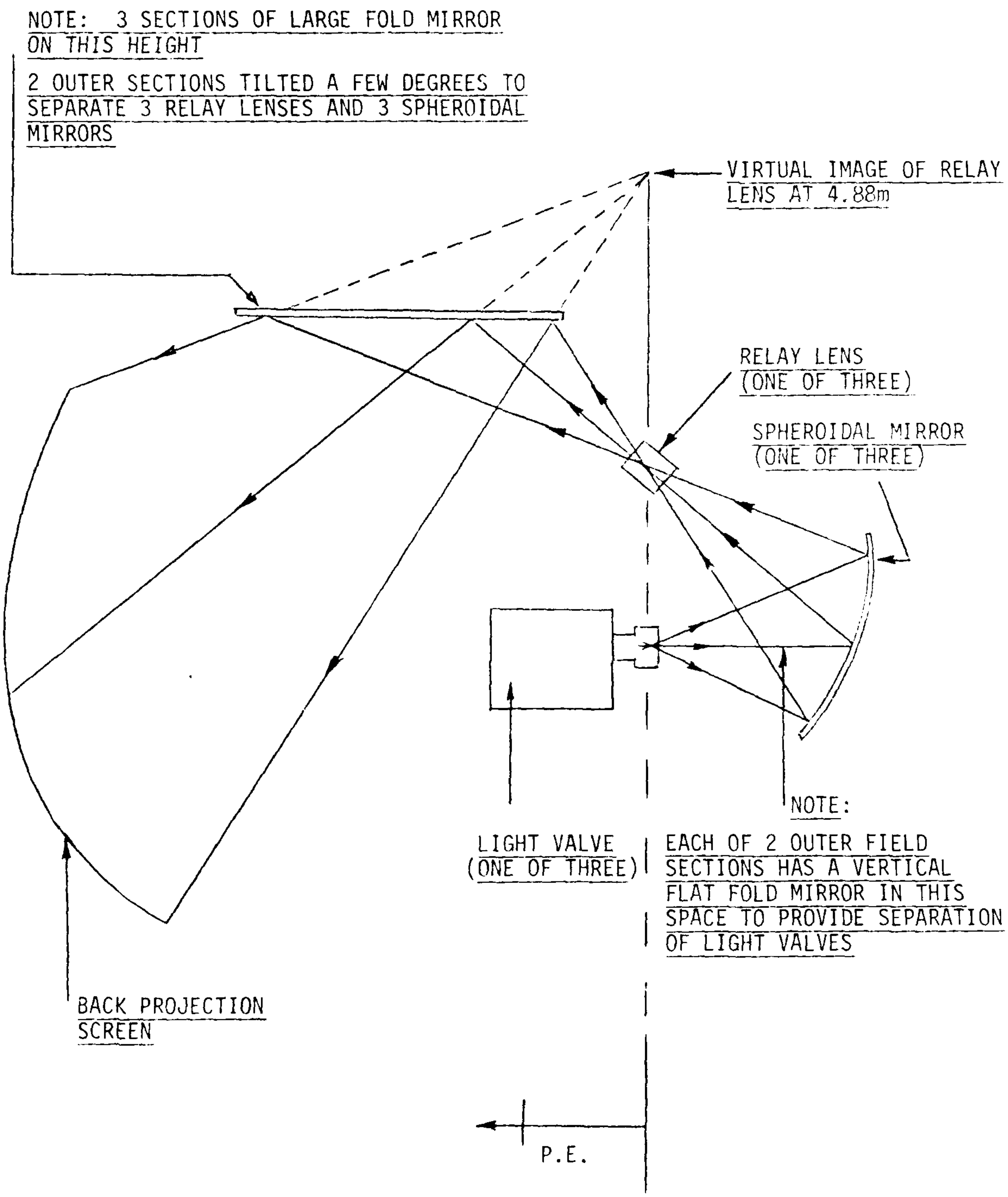


FIGURE 12. PROJECTION SYSTEM USING 3 OIL FILM LIGHT VALVE PROJECTORS WITH SPHEROIDAL DISTORTION-CORRECTION MIRRORS

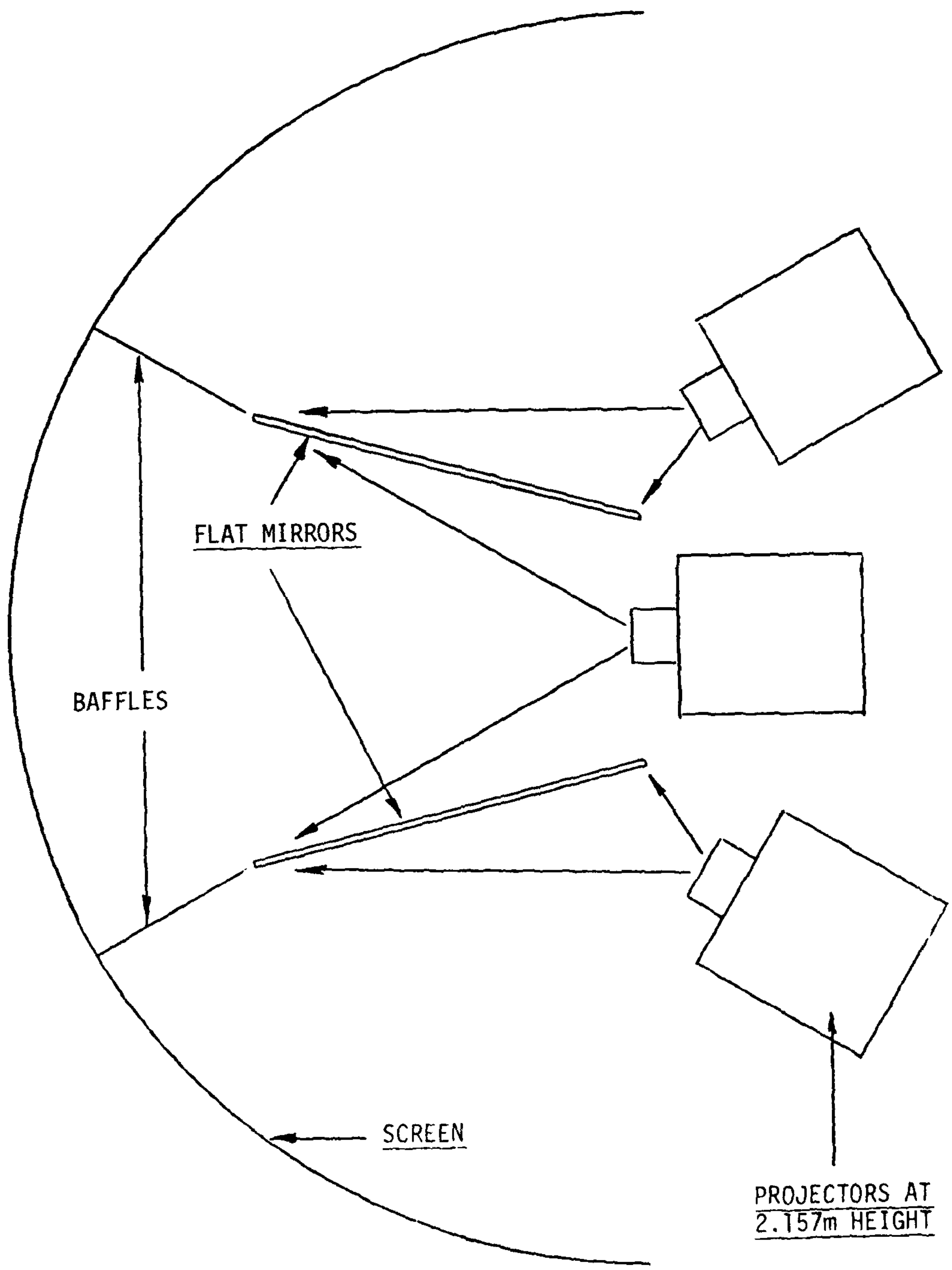


FIGURE 13. PROJECTION SYSTEM USING 3 KDP PROJECTORS

TABLE 9 - SUMMARY OF EXPECTED DISPLAY PERFORMANCE

PARAMETER	DESIGN GOAL	DISPLAY PERFORMANCE
Field of View	180^o x 60^o decreasing to 20^o vertical at 90^o inboard	180^o x 60^o
Viewing Volume Nominal Pilot Head Position With This Volume	1.52 m x 0.91 m x 0.46 m 0.61m from display center line	1.52 m x 0.91 m x 0.46 m 0.61 m from display center line
Head Motion	15 cm radius sphere from nominal pilot head position	30 cm cube located centrally on nominal pilot head position
Geometric Distortion	5% max	Max 5% within tapered field and nominated head motion
Collimation error	Zero convergency to 3 mr divergence max 3 mr dipvergence	Within design goal except for head position outboard, down and forward, whre convergence is positive on inboard side to 1.5 mr and dipvergence goes to 6 mr
Resolution	4 arc min per line center 6 arc min per line corner	2.5 arc min per line center and corner with Scan Laser, 4 arc min per line center and 6 arc min per line corner with KDP crystal light valve
Highlight Brightness	6 foot-lamberts	6 foot-lamberts with scan laser, 12 foot-lamberts with KDP light valve projector
Brightness	Less than 50%	Nominally less than 50% with scan laser may be higher with other projectors and special screen structures
Contrast Ratio	20:1	Worst case 20:1 with Fresnel structure rear projection screen

TABLE 9 - SUMMARY OF EXPECTED DISPLAY PERFORMANCE (Concluded)

PARAMETER	DESIGN GOAL	DISPLAY PERFORMANCE
Joints	Less than 5 arc minutes	less than 5 arc minutes
Image Registration	Less than 10 arc minutes	With separate projector options dependent on accuracy of raster control; No registration errors with scan laser
Color	Minimal color shift	No color shift or variation with scan laser - other projectors minimal
Mapping	Linear image to pilot using linear scanned TV input device raster distortion up to 10%	10% raster distortion to counter non-linearities but needs vertical scaling factor in image generator for KDP light valve projector. Scan laser will require spherical mapping in image generator. In fact spherical mapping may be required with all projectors.

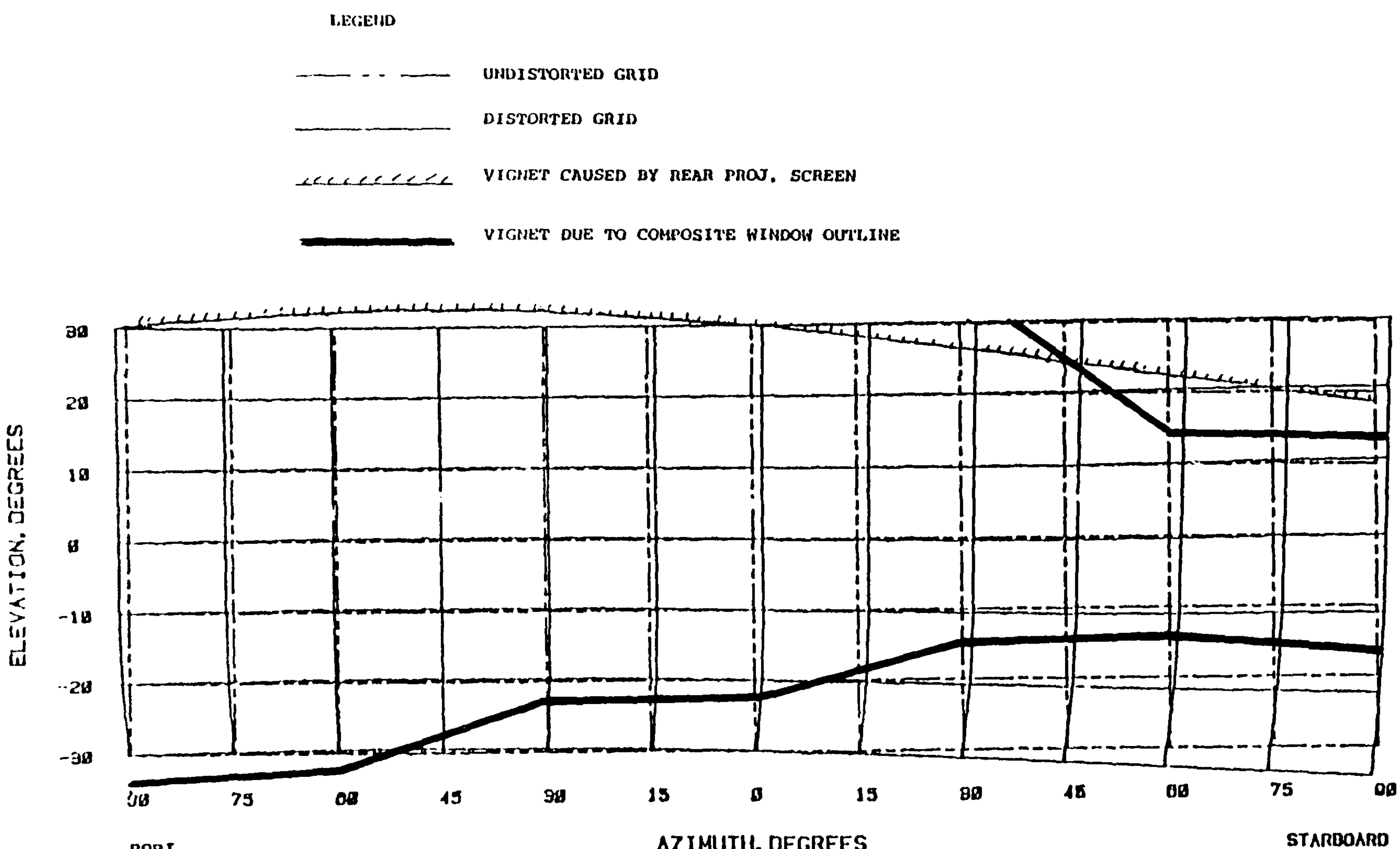


FIGURE 14. GEOMETRIC DISTORTION

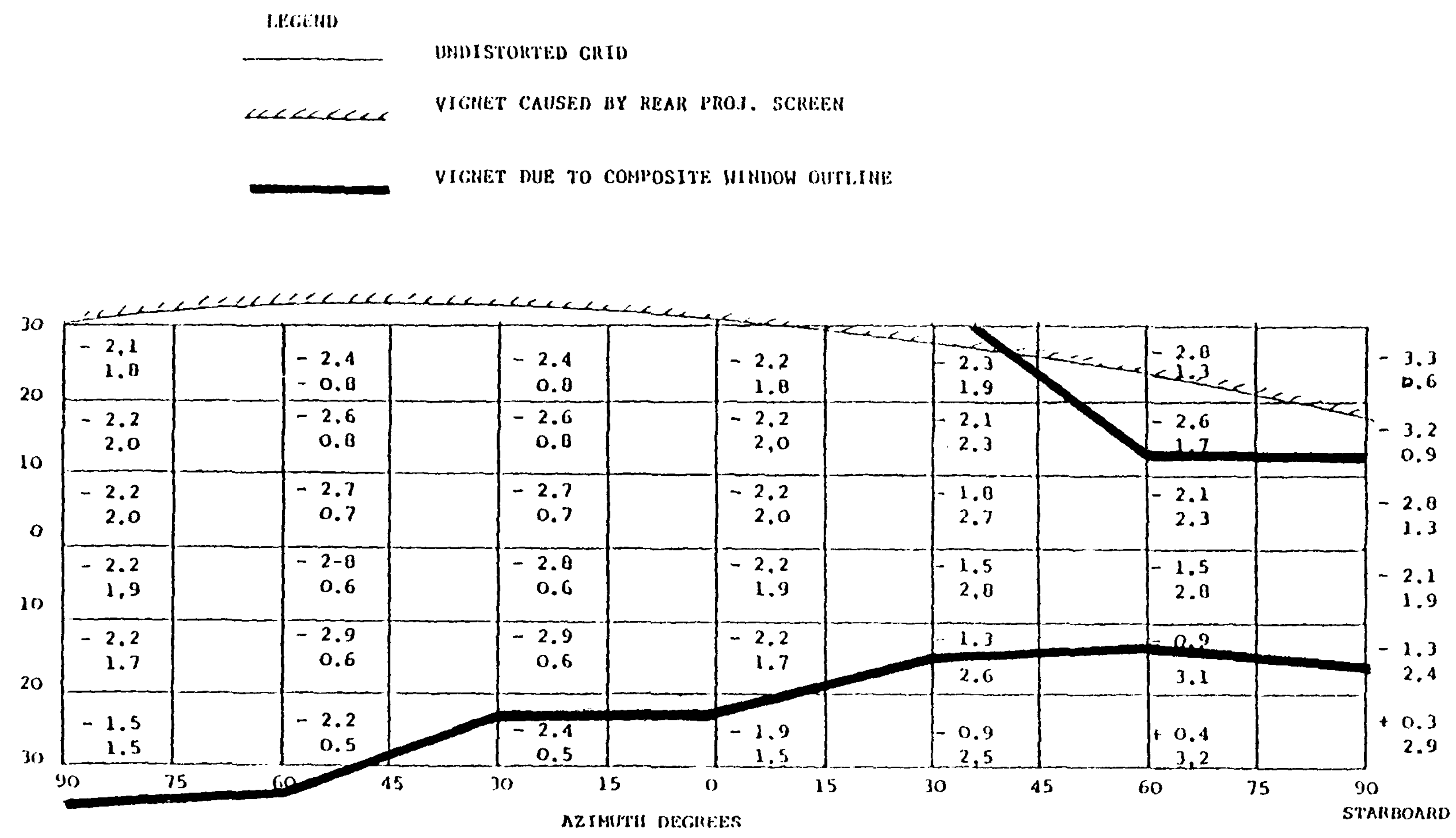


FIGURE 15. COLLIMATION ERRORS

TOP NUMBER CONVERGENCE

BOTTOM NUMBER DIPVERGENCE

2.0 SPECIFICATION OF FINAL DESIGN.

2.1 General Approach to the Optical Design. The design task divides conveniently into two parts.

2.1.1 Design of Collimation Optics. This comprises the size, location, and general shape of the collimating mirror and rear projection screen and the location of the viewing volume.

2.1.2 Design of the Projection Optics. This includes selection of the projector type, location of projectors, any optics between projector and screen and the fine structure of the rear projector screen.

This division is justified, since the collimation optics and projection optics tend to determine distinct sets of performance parameters.

Collimation optics alone dictate viewing volume field of view, and collimation errors, plus the major part of uncontrollable geometric distortion. The projection optics determine resolution, contrast ratio, image joints and registration, color and color convergence, plus most significant factors deciding brightness and brightness variation.

There is some need to consider the effects of collimation optics design on projection systems. Screen location and shape have a significant influence on projector depth of field requirements, and also on amounts of distortion compensation. There is also a marginal effect on the manufacturing difficulty of the light-deflecting fine structure which is needed on the screen in some designs.

2.2 Collimation Optics Design Method.

2.2.1 Basic Assumptions. Based on the result of the previous designs carried out for AFHRL, it is assumed the collimation optics consist only of a rear projection screen, a spherical mirror and a location for the viewing volume. No attempt has been made to extend this concept to include refracting correction or other elements. The effect of simulator cockpit windows are not considered. The mirror is assumed to be continuous and front surface coated.

The design methods used permit the viewing volume to be located anywhere with respect to the center of curvature of the collimating mirror, although in practice the optimum position has been defined by AFHRL. It has been assumed throughout that the collimating system, including the viewing volume, will be symmetrical about a vertical plane running through the simulated aircraft centerline.

The rear projection screen is assumed to have a vertical axis of symmetry which passes through the center of curvature of the spherical mirror. This arrangement provides a vertical axis of symmetry for the mirror/screen combination, so that there is a minimal azimuthal change of distortion produced by the collimation optics.

This advantage in the consideration of distortion change with azimuth change is significant, but not absolutely essential, so that different axis positions for the rear projection screen, or not axially symmetrical shapes, could have been considered. However, no significant problems have arisen in design of the collimation optics which could be affected favorably by departing from a center vertical axis at the screen.

2.2.2 Optimization Procedure. Having decided the basic optical component layout for the collimating system as shown in Figure 16, the following procedure for setting up a system design was carried out.

Select:

1. Mirror radius of curvature Rm.
2. Height of mirror center of curvature above pilot nominal location Ym.
3. Nominal pilot separation from center vertical plane X in this case 0.6 m. (See Figure 16)
4. Vertical field-of-view from pilot location in the forward direction T, B in this case +30 degrees to -30 degrees. (See Figure 16)
5. Azimuths of three rays, with vertical angles 30 degrees, 0 degrees, and -30 degrees for which to compute ideal screen position.
6. Deliberate defocus on each of these three rays, to adjust convergence/divergence.

Then compute:

1. Pilot position Z, in aircraft centerline direction with respect to mirror center, which gives exactly the required field of view (T,B). (See Figure 16)
2. Screen parameters: center height Ys and radii of curvature Rv, Rh. (See Figure 16)
3. Approximate collimation data: convergence, divergence and dipvergence.

The initial task, which requires an interactive routine, is to determine the unique pilot Z shift and the location for the base of the rear projection screen which gives the required forward field. Having fixed the pilot location, three rays are traced from this location to fix three ideal points on the rear projection screen. One of these rays must be the ray forward to the base of the screen.

Finite (exact) ray tracing was used to fix each ray intercept on the mirror surface, the angle of incidence on the mirror, and the direction of the ray between the screen and the mirror. Distances along the rays between screen and mirror are calculated to give convergence and divergence, thereby defining the focal plane of the mirror at that point. Selected amounts of defocus were added to these distances, and exact screen points were calculated. The unique toroidal screen shape which fits the computed screen points was then computed.

2.2.3 Primary Analysis. After all the essential design parameters were fixed, a first order approximate analysis of collimation performance was carried out. A subroutine was used for computing functions of the primary aberrations of the mirror at each ray intercept, giving only the angle of incidence and plane of incidence from the finite ray trace. This subroutine

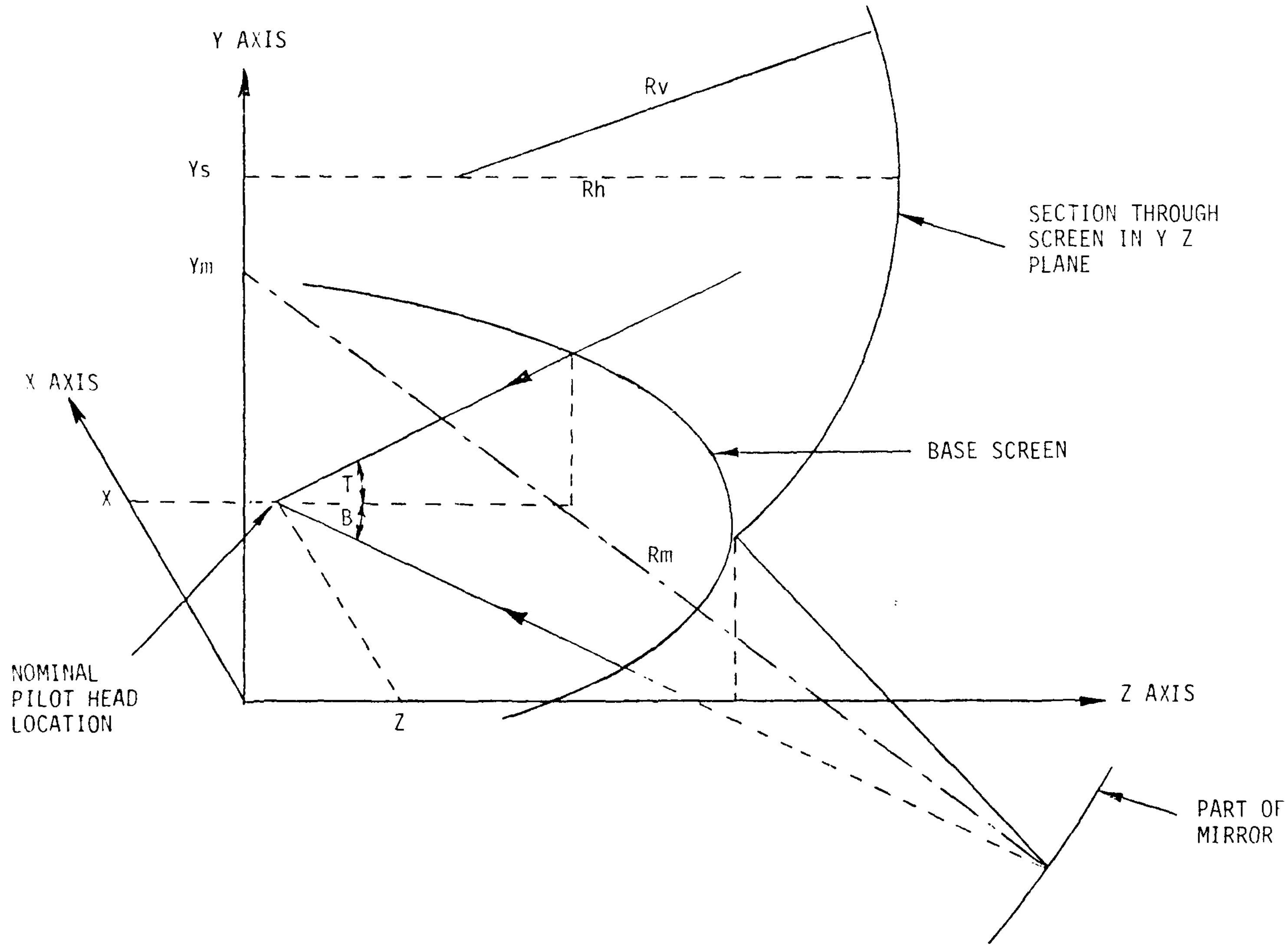


FIGURE 16. DESIGN PARAMETER SKETCH

was needed essentially to calculate ideal screen distances along the ray, taking account of astigmatism. But dipvergence is also easily derived on the assumption that focus is adjusted for zero divergence and convergence. After the screen was fixed, an array of finite rays was traced from the nominal pilot location to the screen. Dipvergence at each field angle and defocus were calculated.

Dipvergence was computed on the assumption that convergence and divergence are near zero, which is not generally justified, but the defocus and dipvergence output together were a useful quick indication of collimation performance. This analysis was not a completely necessary part of the design process, but gave a useful insight to the basic problems of designing the multiviewer.

2.2.4 Optimization of Pilot's Positions. For a given mirror radius, there is a fairly well defined location for the viewing volume. To find this optimum, a set of designs was set up with a range of values for the mirror center height, Ym, using the design program described in section 2.2.2. These designs gave a range of Z shifts for the pilot head location.

For the set of designs, it was necessary to fix all parameters except Ym. The defocus figures for the base, middle, and top of the field of view control the screen shape, as well as having a direct effect on convergence and divergence. Optimum defocus figures must be predetermined, for the set of designs, which give a toroidal screen shape approximating the optimum screen shape on certain criteria (see discussion in section 2.2.5).

Each of the designs generated was run through the analysis program described in section 2.3 below, and the best one was selected.

At this stage, for a given mirror radius, field of view, and viewing volume, and for certain screen shape criteria, an optimum design was determined in all respects, except in general for final adjustment of screen shape.

The process was repeated for a set of mirror radii of curvature, until one optimum design was found to give just- acceptable collimation and distortion. This design will have the minimum acceptable mirror radius, and all other parameters optimized (except for final adjustments to screen shape).

2.2.5 Optimization of Screen Shape. It is generally assumed that the screen will have a vertical axis of symmetry passing through the center of curvature of the spherical mirror. This is regarded as highly desirable to limit azimuthal distortion problems and is not, in practice, found to limit performance in other respects.

However, the shape of the screen in the vertical section can reasonably be varied within wide limits (of order ± 15 cm) to obtain differing performance characteristics.

Screen shape affects collimation errors strongly. It is fairly obvious that outward movement of a section of the screen reduces convergence of light in the associated parts of the scene and increases divergence. The same adjustment has a powerful effect in reducing dipvergence.

Screen shape also affects distortion correction strongly. Tilt and curvature of the screen in the vertical section produce, or correct, tilt and curvature of nominally vertical lines in the display - and these errors are of a kind that cannot be compensated for in the projection system, since they appear in opposite senses from pilot and co-pilot seats. Tilt and curvature also affect the linearity of the image which is ideally required from the projection system, in the vertical section.

Screen shape affects the depth of focus which is required from the projection optics and has some effect on the difficulty of achieving the screen fine structure which is required with most kinds of projection systems.

There is no ideal screen shape. The requirements for minimizing collimation errors conflict with requirements for minimizing distortion, and both conflict with ideal screen shapes considering depth of focus and ease of manufacture. It is necessary therefore to examine the various compromises available and to choose one.

Within the design procedure described in section 2.2.3, screen shapes generated are limited to toroids (with spheres as special cases). These provide a sufficiently close approximation to an ideal shape, based on the selected compromise, to permit optimization of pilot location as described in section 2.2.4.

More complex screen shape may then be investigated. At this stage, it is necessary to consider not only small changes in collimation and distortion performance given by the analysis program described below, but also effects on the projection optics - particularly on distortion required to be generated by the projection optics.

2.3 Final Optimization and Analysis Procedure. Analysis of collimation system designs was then performed by finite ray tracing.

2.3.1 Screen Shape and Object Point Generation. The first step was to compute coordinates for an array of object points in a rear-background screen surface. At this stage it was required to introduce departures from toroidal screen shape, while retaining symmetry about a center vertical axis.

For this purpose screen rays were traced from the nominal pilot head location (usually 0.6 m from the center vertical plane) with initial direction forward (0 degrees in azimuth) at elevations -30 degrees to +30 degrees in 10 degree steps. Intercepts of these seven rays with toroidal surfaces are used to define height (Y) and radial coordinates of object points in a screen surface. In order to permit the shape of the screen to be non-circular in vertical sections, the radius of the toroidal intercept surface is in general different for each of the seven rays. Perturbations in radius of the intercept surface were selected by trial and error to optimize the screen shape in terms of computed system performance.

The Y and Z coordinates of the seven intercept points were taken as the height and radius coordinates of an array of object points. It was assumed that the screen was a surface of revolution about the center vertical axis of the collimator system (which includes the mirror center of curvature). The azimuthal locations of object points in the screen were set at equal 15 degree intervals from -90 degrees to +90 degrees with respect to the screen axis, and the same set of seven height and radius coordinates used at each azimuth, to give seven elevations. (The X coordinates of the screen ray intercepts are discarded).

The array of object points thus generated represent points in a polar coordinate grid, with steps of 15 degrees in azimuth and 10 degrees in elevation. They were selected, without regard to the projection system, to give a polar coordinate grid image to the pilot and co-pilot with minimum distortion on certain arbitrary criteria. The criteria are:

1. There is zero error in elevation of all points nominally forward (0 degree azimuth, -30 degrees through +30 degrees elevation).

2. The azimuthal errors in each image point are equal and opposite for pilot and co-pilot head positions. (An alternative is to offset the object points horizontally to provide better correction for the pilot - but this increases the errors seen by the co-pilot).

All subsequent analysis was carried out by tracing rays through the array of object points generated as described above. This has certain implications for the definitions of distortion and decollimation performance data used in this report, which are detailed in section 2.3.3 below.

The screen surface shape was strictly defined only by the coordinates of the array of object points, since each ray used in analysis of the system passes through an object point. In vertical section, the screen surface could be any curve passing through the seven defined height/radius coordinates - but in practice it is assumed that the curve will be smooth.

2.3.2 Ray Tracing. Finite rays were traced from each of the subject's eye locations to each object point generated as described above.

The eyepoints were taken to be 6.5 cm apart, and equispaced on either side of the defined head location.

The line between eyepoints is always set orthogonal to the nominal viewing direction. (This is the worst case for collimation errors, but merely assumes that the pilot's head will be rotated in azimuth to look squarely at objects, and this will occur, at least occasionally, for all object locations).

The analysis program permitted off-sets to be introduced between the computed head location and the nominal pilot head location. The object array was set up by tracing from the pilot nominal head location, as just described, but subsequent analysis could be carried out for any head location.

Accurate tracing of each ray required an iterative procedure. Successive linear corrections were applied to the ray direction at the eyepoint until the ray intersected the object point to a sufficient accuracy. The ray direction at the eyepoint was then stored.

2.3.3 Distortion and Decollimation Data

2.3.3.1 Collimation System Distortion Plots. (Figures 2 thru 9) The graphical representations of collimation system distortion given in this report are simple cartesian plots of the polar coordinates of viewing angles (azimuth and elevation angles as usually defined). The viewing direction for a given head position and object point is taken as the bisection of the directions computed for the two eyepoints.

Actual viewing angles are plotted. The nominal undistorted polar coordinate grid is also plotted to provide a reference.

The cartesian plot of polar coordinate angles provides a convenient method for representing distortion. It gives a valid impression of some aspects of distortion, particularly tilts on nominally horizontal and vertical lines and magnification variations. Some caution is required however in use of the plots to measure absolute errors. In particular, the difference in the azimuthal angular coordinates of two ray directions at non-zero elevation is larger than the angle between either ray direction and the vertical plane which includes ray direction.

2.3.3.2 Collimation System Distortion Tables. (Table 1 thru 8). The collimation system distortion data tabulated in this report are percentage angular errors between actual viewing directions (for a given system and head location) and nominal viewing direction, for each point in the polar coordinate grid of object points.

Actual viewing direction is taken to be the bisection of viewing directions for the two eyepoints.

Two tables are given for each head location, giving vertical and horizontal errors, respectively. Vertical errors are computed simply as the difference in elevation angles of actual and nominal viewing directions.

Horizontal error is defined as the average angular separation of the two rays from the vertical plane which includes the nominal viewing direction.

Both vertical and horizontal errors are converted to percentages of picture height by multiplying by 100/60 degrees $^{-1}$.

2.3.3.3 Decollimation Data. Convergence and divergence figures are tabulated for each head location analyzed.

Dipvergence is taken simply as the difference in elevation angles of the actual viewing direction for the two eye points, and is computed for each object point. Both dipvergence and convergence figures are converted to milliradians for ease of comparison with the system specification.

Convergence is defined as the difference in angular separations of the two eye rays from the vertical plane which includes the nominal viewing direction. This gives the divergence angle between the pilot's eyes required to fuse the two images (ignoring non-geometrical factors) assuming that the pilot's head is rotated in azimuth to look squarely at the image and also that the head and/or eyes are rotated in elevation to get the images on eye axes defined by foveal regions. Convergence means convergence of light, not of the pilot's eyes. Negative convergence figures indicate divergence of light.

It should be noted that convergence and dipvergence figures are computed for distortion field angles. Thus, the first figure given in each table (#1-8) gives the collimation error for a point in the field which would appear at +30 degrees elevation, 90 degrees to starboard if there were no distortion.

2.4 Design for Minimum Mirror Size

2.4.1 Criteria. A system which meets the Air Force specification, on any reasonable interpretation, must necessarily be very large compared with existing flight simulation display systems.

The preferred design is therefore one which is specified in detail to permit the smallest possible collimating mirror consistent with performance which may be considered just- acceptable.

The following detail design criteria were selected:

Viewing Volume: The specified collimation and distortion performance at nominal pilot and co-pilot head locations were ±0.6 m from the simulator center vertical plane.

Field of View: Vertical field ±30 degrees at all azimuth angles, 0 degree and 90 degrees outboard; reducing to +18 degrees, -30 degrees at 90 degrees inboard, these figures applying to pilot and co-pilot nominal head locations.

Collimation: The dipvergence was to be less than 3 mr, and light convergence between 0 and -3 mr, for the nominal pilot and co-pilot head locations, assuming 6.5 cm eye separation, within that part of the field of view ±30 degrees in elevation from 0 degree to 90 degrees outboard in azimuth, tapering to ±10 degrees in elevation between 0 degree and 90 degrees inboard in azimuth.

Distortion: Distortion generated by screen and mirror minimal consistent with achieving minimum system scale and stated specification on viewing volume, field of view, and collimation.

It will be noted that these criteria do not meet the Air Force minimum specification on a strict reading. Collimation errors for head locations up to 15 cm outboard from the nominal mean locations will exceed 3 mr.

Distortion errors contributed only by the collimation system, and not compensatable in the projection system, will be within the Air Force specification, within the tapered field.

2.4.2 Preferred Design. Parameters of the preferred collimating system design are tabulated below. Figure 17 shows the parameters. The X, Y and Z values for mirror, screen and viewing-volume locations are cartesian coordinates with respect to common axes. The Y axis is vertical, passing through the mirror center of curvature. The Z axis is parallel with the simulated aircrafter centerline and is on a level with nominal pilot and co-pilot head locations.

Mirror radius of curvature: 5.18 m

Mirror center of curvature location:

X	0
Y	2.460 m
Z	0

Screen surface coordinates in Y, Z vertical plane at nominal elevations -30 degrees to +30 degrees on 10 degree steps:

	Y	Z
(-30°)	1.016 m	2.432 m
	1.265	2.77
	1.648	3.024
(0°)	2.157	3.161
	2.7	3.188
	3.246	3.101
(30°)	3.774	2.888

Pilot nominal head location:

X	0.6 m
Y	0
Z	0.6 m

As in all designs, the back projection screen is a surface of revolution about the Y axis. The shape is non-circular in the vertical sections through the Y axis, so that screen shape is defined in this case only by the coordinates of points in these sections (corresponding to object point locations used in analysis).

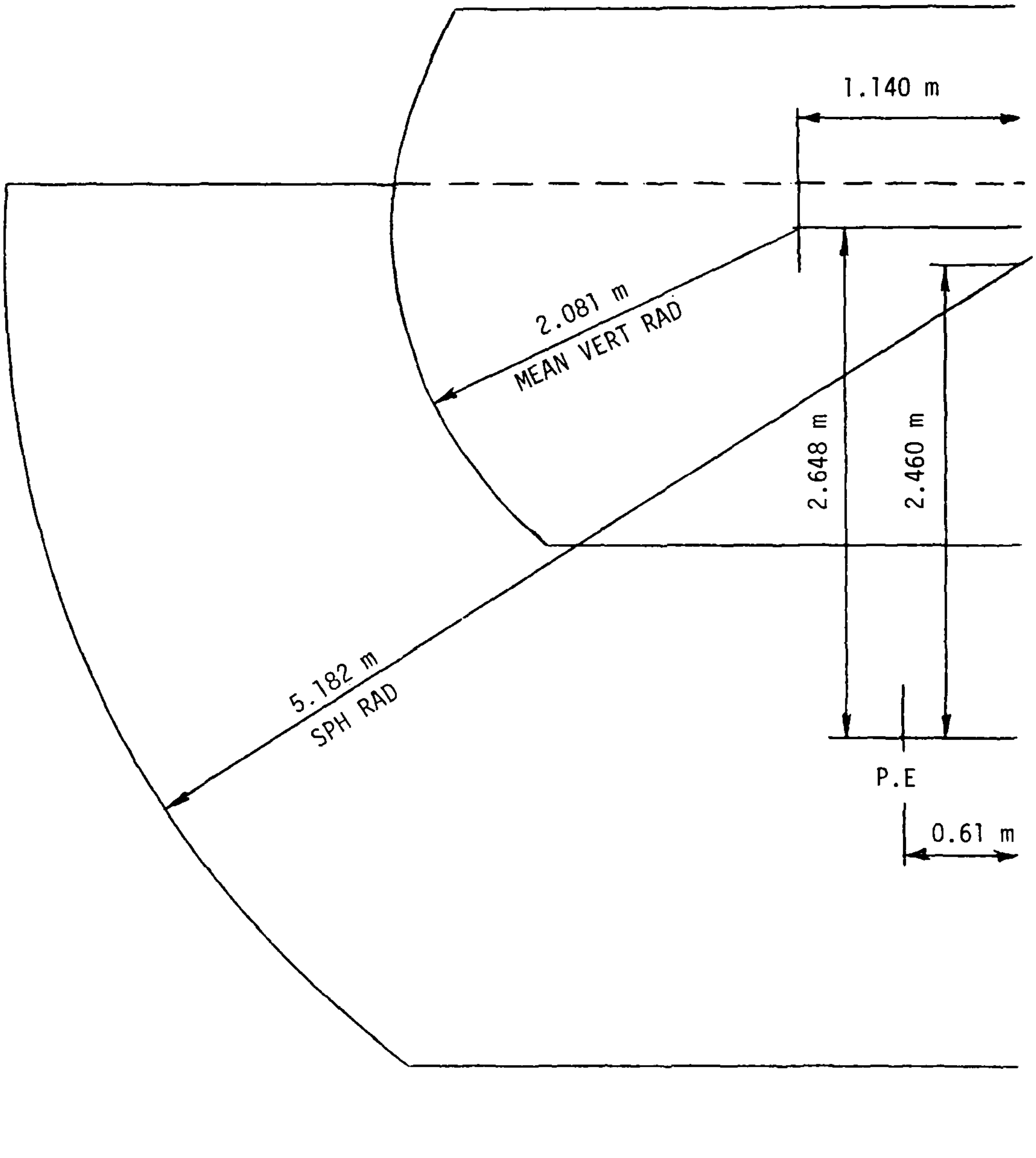


FIGURE 17. 180° WIDE ANGLE MULTIVIEWER MIRROR SCREEN CONFIGURATION VERTICAL SECTION

2.5 Performance

2.5.1 Distortion and Collimation - Tables. Distortion and collimation errors for the system are given in Tables 1 to 8. Each table gives data for a different head location within the viewing volume. Head locations are specified with respect to the nominal pilot head location. Thus, for example, zero X, Y and Z offsets refer to the pilot's head location, and offsets (0.15, -0.15, 0.15) refer to the forward lower corner of the viewing volume on the pilot side.

Distortion and decollimation errors are given for each of an array of object points at the screen, at nominal elevation angles from -30 degrees to +30 degrees in 10 degree steps and nominal azimuth angles from -90 degrees to +90 degrees in 15 degree steps.

Errors are defined in sections 2.3.3.2 and 2.3.3.3 above.

With allowances made for reduced field across the cockpit, distortion errors are within specification for whole viewing volume. Decollimation figures are just within specification for the pilot and co-pilot nominal head locations. Decollimation is within specification for small offsets in head location inboard, upward, and rearward, and out of specification for offsets outboard, downward, and forward. For head locations close to the system vertical axis, however, although the dipvergence correction is very good, divergence is outside specification.

2.5.2 Distortion - Diagrams. Figures 2 through 9 show distortion produced by the preferred collimation system design. Distortion was plotted for each of eight head locations within the viewing volume. Distortion as plotted is defined in section 2.3.3.1 above.

For accurate distortion data, the tables should be used. The diagrammatic representations are of value in indicating some aspects of distortion which could prove objectionable even though they are well within specification. Particular attention is drawn to four distortions seen from the nominal pilot and co-pilot head locations:

a. Horizontal offset of the center of field, of 1.4°.

b. Curvature of vertical between -10° and -30° elevation.

c. Tilt of the mid-field horizontal of 0.9°.

d. Variation in tilt of horizontals with elevation.

2.5.3 Field of View. Part of the field of view for which distortion has been computed will in general be masked by c ckpit structures.

The system is designed to meet the minimum specification set out in section 2.4.1.

2.6 Validation of Analysis Program. The analysis program used is crucial to confidence in the present design exercise and it has accordingly been checked very carefully. Reliance for validation is placed mainly in a check using a different ray trace program run on a different computer. Rays were traced to five different points in the field of view, from each of five different pairs of eye locations, using starting directions generated by the analysis program. Ray intersections at the screen checked with nominal object point locations to $\pm$ 0.0002 feet which is within the final accuracy written into the analysis program interactive routine.

2.7 Analysis Program Comparison Against Preceding Studies. The final designs from the preceding studies (Shaffer and Waidelich, 1977; Rhinehart, 1977) have been run on the analysis program. There is agreement between convergence and divergence results to within 0.2 milliradian reported by Shaffer & Waidelich (1977). Some small differences may be due to different methods of specifying field angles at which decollimation is computed. This report does not include figures for dipvergence nor sufficiently precise data on distortion to permit a cross check.

The results obtained from the system described by Rhinehart (1977) are not in agreement with the analysis program and no obvious explanation for the discrepancy has been found.

3.0 PROJECTION SYSTEM

3.1 Overview of Projection System. Now that the rear projection screen shape has been defined, the type of fine structure on the screen surface is dependent on the projection device chosen. A large number of projectors are available or under development and have been investigated. Basically projectors fall into three main groups:

1. Light valve projectors using either oil films, liquid crystals, or Pockels cells as light modulating devices.
2. Projection cathode ray tubes.
3. Scanned laser systems.

The following sections will discuss the various projector types and how they may be incorporated into the Wide-Angle Multiviewer display optics.

3.1.1 Oil Film Light Valve Projector. Two types of oil film light valve projectors are available. One uses three separate light valves, one for each color: red, green, and blue. The other type uses a single light valve to produce the three colors. Both types use a high intensity xenon arc lamp as the light source. The image on both types is produced by Schlieren optics in conjunction with an oil film distorted by electron beam raster scanning. The three tube projector uses the oil film in a reflective mode with color filters. The single tube device uses the oil film in a transmissive mode and high frequency modulation of the electron beam to form a phase diffraction grating on this film with associated filters in the exit pupil.

Both types are available in versions operating on 1000 line scanning systems, and the single light valve projector has been used in many flight simulator display systems. Some basic parameters of these oil film light valve projectors are detailed in Table 10. With reference to Table 10 and from a consideration of light output, the three-tube projector would be a possible contender for the Wide-Angle Multiviewer, but the size, weight, and minimum throw distance rule this device out immediately.

The single light valve version is not so easily dismissed. Although the light output is less than one-tenth of three light valve output (see Table 10), it has the same resolution, is conveniently packaged and has good depth of field associated with the small exit pupil diameter. Also this projector is well known in the simulation industry and is easily available "off the shelf." A disadvantage of this projector is that because of the methods by which color light modulation is achieved, significant distortion correction by raster control is not possible.

3.1.2 Pockels Effect Light Valve Projector. This projector is a recent development of the light valve type using the Pockels effect in a KDP (an acronym for KH^2PO^4) target which is raster scanned by an electron beam. Three separate targets are used to produce the three primary colors (red, green and blue) for a full color display. A system of dichroic mirrors splits up the incident light from a xenon arc lamp and also recombines the reflected beams carrying the picture.

TABLE 10 - OIL FILM LIGHT VALVE PROJECTOR PARAMETERS

	Single Tube	3 Tube
Maximum Line Standard	1023/60	945-60
Horizontal Resolution Lines/ Picture Height	800	800
Light Output Lumens	600	7000
Contrast Ratio	75:1	100:1
Max Field Angles with Current Lenses	35.8° x 27.2°	27° x 20.3°
Exit Pupil	Approx. 13 mm	N/A
Distortion % Per Picture Height	2%	1%
Min Throw distance at Max Field Angle	1 m	10 m
Projector Head Size	0.56 m x 0.43 m x 0.81 m	2.07 m x 1.03 m x 1.54 m
Projector Head Weight	64 kg	500 kg

The first version of this projector demonstrated was in a 625-line standard configuration with a light output of 2700 lumens. The projector was bulky and relatively inconvenient to use due to the space requirements of the optical system. Since this first demonstration several years ago, considerable development efforts have been undertaken by the manufacturer to repackage the projector head and increase the resolution performance. Table 11 gives an indication of the current performance of this projector. The Pockels effect projector is currently being developed for flight simulator applications and future developments are proposed to increase the horizontal resolution and use 1000 line standards. The advantages of this projector are as follows:

1. High luminous output should ease the construction of the rear projection screen, to give sufficiently high brightness at large deflection angles.

2. Raster control to provide distortion correction will be feasible.

3 The square format will permit efficient usage of the device, assuming the field is divided into 60° by 60° sections.

The following advantages are associated with image generator sources:

1. The scanning system is linear and not resonant, therefore enabling a wide range of compatible image generation sources to be used.

2. The display is inherently flicker free so frame rates are decided on update rates and not flicker suppression. This enables lower frame rates to be used with high line standards thereby keeping the video bandwidth down.

3. Frame storage facility available.

The disadvangates are as follows:

1. Development of the high resolution (1000 line system) is at an early stage, leaving some doubts on performance.

2. Depth of field is fairly restricted.

3.1.3 Liquid Crystal Light Valve Projector. The Liquid Crystal Light Valve projector was developed for flight simulator applications and to be used in the Advanced Simulator for Pilot Training (ASPT) as a replacement for the 91-centimeter cathode ray tubes. This basic method of operation of the projector is similar to the device described in section 3.1.2 except the KDP crystal is replaced by a liquid crystal in conjunction with a fiber optic faceplate CRT.

Performance of the developed projector is shown in Table 12. The expected performance of this projector would meet the requirements of the Wide-Angle Multiviewer resolution specification but the expected light output is lower than required.

TABLE 11 CURRENT PERFORMANCE ON THE KDP LIGHT VALVE PROJECTOR

	Current Performance
Line Standard	625
Horizontal Resolution	950
Light Output Lumens	2500 polarized
Contrast Ratio	60:1
Field Angle up to	$90^{\circ} \times 90^{\circ}$
Exit pupil diameter 30° field	Approximately 80 mm
Projector Head Size	1 mm x 0.8 m x 0.7 m
Projector Head Weight	150 kg

TABLE 12 PERFORMANCE OF PROTOTYPE LIQUID CRYSTAL LIGHT VALVE PROJECTOR

	Performance
Brightness Lumens	Greater than 216 polarized
Contrast Ratio	20:1
Rsolution T.V. lines	1000 at 30% MTF
Geometric Distortion	0.5%
Field Angle	90^o x 90^o
Projector Head Size	1.6 m x 0.96 m x 0.43 m
Projector Head Weight	136 kg approx.

A visit to the manufacturer was undertaken to see this projector but at the time it was not working. There had apparently been problems with excessive light loss in the optics and the system was partly dismantled for investigation. Also difficulties had been experienced with the manufacture of the liquid crystals. The manufacturer also stated that there were no plans to continue development after the present contract had been completed.
The color projector still requires considerable development funding before it becomes a viable commercial proposition, and it did not seem as if it would be pursued, at least by the initial manufacturer. A monochrome version was available as a commercial projector for the data display industry.

With this situation it was therefore not considered further for the Wide Angle Multiviewer.

3.1.4 Cathode Ray Tube Projection System. There is a wide range of CRT type projectors available or in development from a very sophisticated version using sapphire face plates down through liquid-cooled face plate devices down to domestic projectors. The vast majority of these projectors can be dismissed with regard to the multiviewer requirements for the following reasons:

1. Insufficient light output - most projectors have a light output of less than 100 lumens.

2. Insufficient resolution - majority of the projectors are designed for commercial and domestic applications where 400 TV line resolution is sufficient.

3. Relatively low specification on geometry, convergence and long term stability - although sufficient for their intended applications are not up to standard demanded by the multiviewer.

4. Projectors with higher brightness than 100 lumens achieve this by optics with exit pupil diameters in excess of 25 cm and would cause major design problems associated with their extremely short depth of field.

This leaves two basic types of projectors: one using a sapphire face plate and the other a liquid cooled face plate. The sapphire face plate version has up to 1000 line resolution with 1000 lumens output but again has a large exit pupil with attendant low depth of field. The device is also physically large compared with other projectors examined other than the three tube oil film light valve projector.

The final CRT type projector examined was the liquid-cooled face plate version. The projector is still under development but has the potential of 1000-line resolution and 350-lumen light output. This projector is fairly unique and, by using a liquid-filled cavity interfacing the three projection tubes with a single output lens, many of the problems associated with three tube projectors, such as physical displacement of color outputs and low brightness, are solved. Although no figure has yet been obtained on the exit pupil size, it must be at least 12 centimeters and probably higher. This size of pupil coupled with a low throw angle again pose considerable problems with optical distortion correction and depth of field.

The projector is at present not commercially available, and when, if ever, it will be is not known. This, coupled with the possible depth of field problem, rules out the projector at the present time.

3.1.5 Laser Scanned Projector. The idea of producing a projector based on a modulated scanning light beam has existed for some time, but it was not feasible until the availability of high power visible light lasers could produce a sufficiently small and intense beam. This type of projector is theoretically capable of high brightness and very high resolution - resolution being ultimately dependent on the ability of optics to focus the laser beam. All the projectors discussed previously have been limited in resolution by phosphor characteristics or high intensity electron beam focusing, or both; the scanned laser suffers from neither of these.

Scanned lasers have been used in film recording devices and also proposed for flight simulators.

The projector type considered for the multiviewer is very similar to the experimental laser projector operating in Rediffusion Simulation LTD's (RSL's) development laboratories.

Beams from two lasers, blue and green from argon and red to a krypton laser, are intensity modulated at acousto-optic modulators, combined, and raster scanned across the display screen by optomechanical devices. Expected performance parameters for this device configured for application to the multiviewer are listed in Table 13.

Advantages of a laser system for the multiviewer application include:

1. High Resolution.

2. Very small exit pupil which gives a depth of field permitting projection onto the screen at oblique angles, reducing the need for special screen structure.

3. Easy correction of distortion by oblique projection.

4. Continuous raster scan around the full field, eliminating discontinuities in picture information and brightness with good brightness uniformity.

5. Inherent color convergence corrected.

Disadvantages are:

1. Further development required to optimize performance.

2. Laser speckle may be a problem.

3.2 Preliminary Projector Choice. On a first pass basis, the projectors that look as if they could be configured for the multiviewer are the single tube

TABLE 13 EXPERIMENTAL AND EXPECTED PERFORMANCE OF SCAN LASER PROJECTOR

	Experimental Performance	Expected Performance
Light Output Lumens	100	600
Contrast Ratio	12:1	50:1
Resolutions:		
Vertical TV Lines	1200	1500
Horizontal TV Lines	5280 - Vert Scan Lines	5280 Vert Scan Lines
Geometric Distortion	Less than 0.5%	Less than 0.5%
Field Angle	175' x 60^{o}	175' x 60^{o}
Exit Pupil	0.9 mm	0.9 mm
Projector Head Size	N/A	1.42 m x 1.016 m x 0.82 m
Projector Head Weight	N/A	270 kg

oil film light valve, the KDP light valve, and the scanned laser projector. The first projector was chosen because it is readily available and has reasonable light output and resolution and also good depth of field. The second projector was chosen because it has high light output, high resolution, good geometry control and reasonable depth of field. The third projector was chosen because it has very high resolution, very good depth of field, only a single projector is required for the full field-of-view and reasonable light output.

Although the latter two projectors out perform the first one with regard to resolution and versatility, they are still development devices whereas the first projector is well known and well tried, so merits at least initial comparison with the other two.

Before a final choice between these projectors is made, their possible configurations and performance implications to the multiviewer will be discussed.

3.3 Basic Photometric Considerations - Screen Gain. A main problem in design of the multiviewer is to achieve good display brightness and contrast ratio. The screen area to be filled is necessarily large; rear-projection screens are normally inefficient, and will be less than normally efficient in the multiviewer because of large angles between the screen surface and required ray directions.

Taking the specified minimum highlight brightness (6 foot-lamberts) and the area of the screen in the preferred design (25 m^2), if the screen gain is G, then the total luminous flux required from the projectors is about 2000/G lumens allowing for losses in other elements.

Given a high-output projector system, it will be possible to work with a relatively low screen gain. Three KDP projectors will give a usable output of up to 7500 lumens. With these projectors, the screen gain may be well below unity. Alternatively, a version of the projector with lower light output would be used.

Using three presently available oil film light valves, the usable light output (allowing for loss of 25% of each 4:3 format and 30% loss through folding optics) will be 1350 lumens. This would require a screen gain of about 2.

A laser projector, assuming 600 lumens output, would require a screen gain of about four.

Peak white brightness will in practice be non-uniform around the screen area, particuarly in the case of the light valve types which will sub-divide the field. If the brightness specification is taken to refer to the lowest peak white figures, then higher screen gains must be estimated. These would be, say, four for a laser system, three for the oil film light valve, and unity for the third projector.

3.4 Projector Locations

3.4.1 Axial Locations for Multiple Projectors. There are significant advantages to be gained by locating the projector exit pupils close to the vertical axis of symmetry of the multiviewer optics (which includes the screen axis and the mirror center of curvature).

First, if the projector exit pupils are grouped close together, there is minimum brightness discontinuity at joints between the picture sections which are projected from the pupils. There is also a minimum requirement for azimuthal scatter at the screen, with some marginal advantage in screen gain.

Second, if the projectors are close to the axis, it becomes possible to set baffles between the projected beams as indicated in Figure 13. These baffles will greatly reduce the problem of stray light in the cavity behind the screen, improving the display contrast ratio.

Finally, axial location of projectors reduces to a minimum the problem of distortion correction for the projector system. Given axial location, all vertical lines in a display are produced by straight lines from the projector. The azimuthal separations of vertical lines also require no correction in the projector system. If the projector axes are also horizontal and on a level with the projected horizon line (for level flight), then all horizontal lines in the display are best produced by straight lines from the projector. The residual distortion requirement in this case, for the preferred design, is illustrated in Figure 18. The diagram shows the shape of a grid which would be required on a flat projector object surface (oil film or KDP slice) to produce a best polar coordinate grid, 60° in azimuth by 60° in elevation, in the display. This is compared with grids which would be produced on the object surface (a) with no attempt at any distortion compensation and (b) with simple vertical scaling.

Note: The grids show lines of longitude and latitude, so that only the horizon line is intended to be a straight horizontal line.

It is also assumed that there is no distortion in the projector lens. The residual distortion requirement is vertical non-linearity. This could be produced in the KDP projector by raster control, but is too large to be produced by raster control in the other light valve.

3.4.2 Field Angle Problems - Multiple Projectors on Axis. Location of projector exit pupils close to the axis of the collimation system requires large field angles- approximately 60° x 60° assuming that three projectors are employed. The light valve types are not at present equipped with wide-angle optics, so that axial location will require some new design and development.

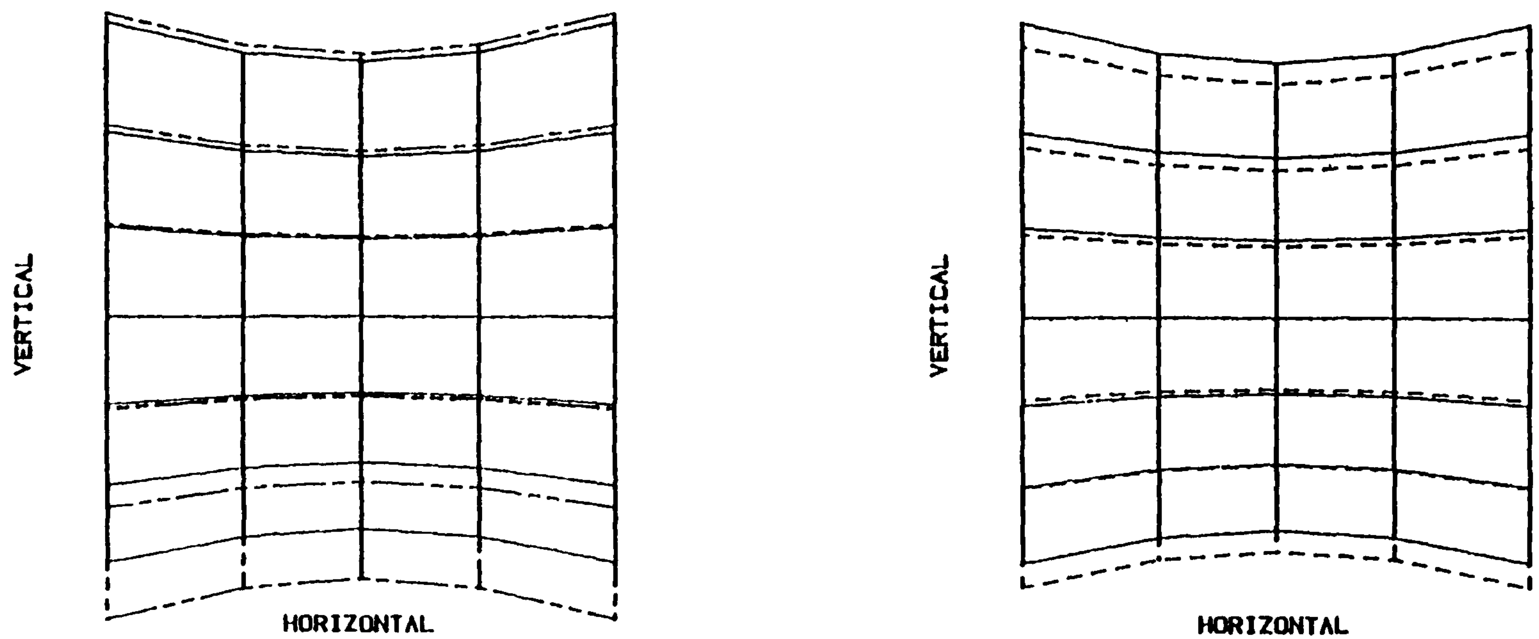
The manufacturers of the KDP projector state that field angles up to 90° square are a requirement of flight simulation; therefore, it can be assumed that a 60° square field can be generated. Because of the large exit pupil of this projector, the optics necessarily will be large and costly and may also suffer from a certain amount of pincushion distortion.

PROJECTOR IDEAL DISTORTION,

PROJECTOR LOCATION METERS: Y 2.157 Z Ø

COMPARISON WITH UNDISTORTED GRID

COMPARISON WITH VERTICALLY SCALED GRID



——— IDEAL DISTORTED GRID

- - - - UNDISTORTED GRID

——— IDEAL DISTORTED GRID

- - - - VERTICALLY SCALED GRID

FIGURE 18

The other light valve projector optics can certainly be modified to give a 60^{0} square field (with some masking to reduce the 4:3 format to 1:1).

Optical design and construction would be expected to be straight-forward, though not trivial. Preferably the new optics would be designed integrally with the internal optical system, which could not be modified, but this presents some problems of commercial confidentiality.

3.4.3 <u>Rearward Shift of Multiple Projectors</u>. Field angle requirements at multiple projectors can obviously be relaxed by projecting onto the screen from greater distances - across the axis of the collimation system.

Distortion requirements for longer throw distances are illustrated by the computer plots, Figures 19 and 20. These show ideal distorted grid shapes required (again for 60^{0} x 60^{0} grids in polar coordinates, and assuming no projector lens distortion) on flat object surfaces, for the preferred collimating system design. The projector locations are calculated for maximum horizontal field angles of 30^{0} and 45^{0}, respectively. The main change in distortion requirement is barrel distortion, and there is also an element of keystone distortion. Problems caused by this change of distortion requirement, on shifting the projectors away from axis, are associated less with absolute percentages needed (though these increase) than with increased complexity of distortion functions. Vertical non-linearity, the only compensation required from axial locations, is mathematically very simple, and simply produced by either electronic or optical hardware. Barrel and keystone distortion are much more complex.

For these reasons associated with distortion correction, and for the photometric reasons (brightness uniformity and contrast ratio) noted in section 3.4.1 above, it is most likely that multiple projectors will be grouped around the axis of the collimation system.

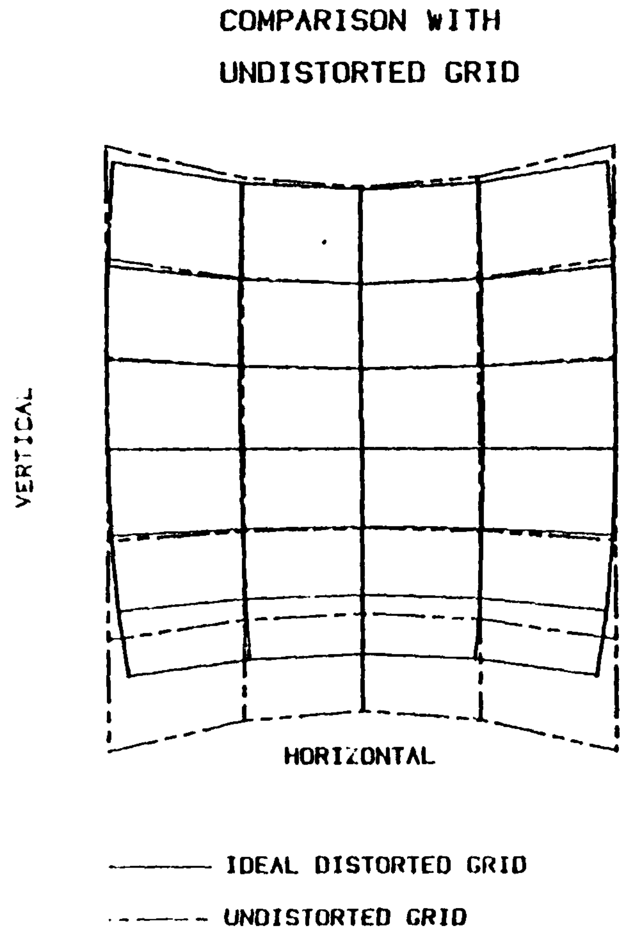
In the case of the KDP projectors, the conclusion follows from the assumption that 60^{0} square field optics, with reasonably good correction, will be made available, designed or modifiable for a curved screen. Axial location is particularly attrative in this case because of better brightness uniformity and control of stray light. (Some electronic raster control to compensate for pincushion distortion in the projector lens might be necessary, in addition to simple raster control to compensate for vertical non-linearity).

3.4.4 <u>Straight-Through Projection</u>. The projector locations considered so far are on a level with the horizon image at the screen (for level flight). These locations are natural choices since they give minimum distortion-requirements in the projectors. However, with projectors at the horizon level, it is necessary for the screen to deflect useful light through angles up to around 60^{0}, at whatever gain is required by the particular projectors considered. This certainly requires development of a special screen structure, and such developments can prove very difficult and costly.

High locations for projectors reduce the deflection of useful light required at the back-projection screen, and thus reduce or eliminate the need for a special screen structure development.

PROJECTOR IDEAL DISTORTION.

PROJECTOR LOCATION METERS: Y 2.157 Z -1.078



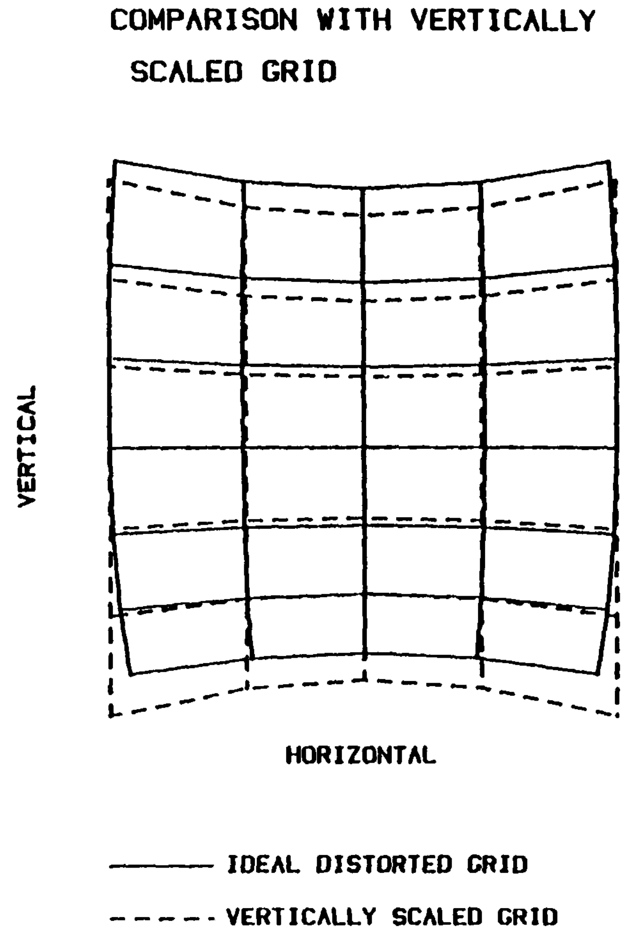
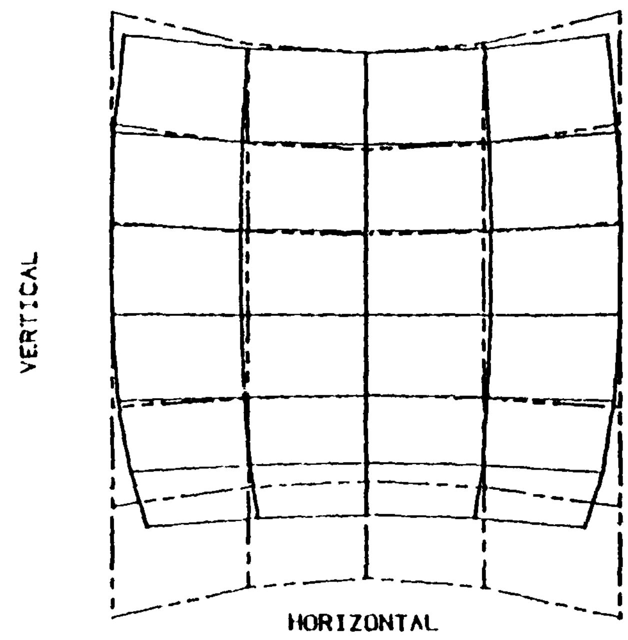


FIGURE 19

PROJECTOR IDEAL DISTORTION.

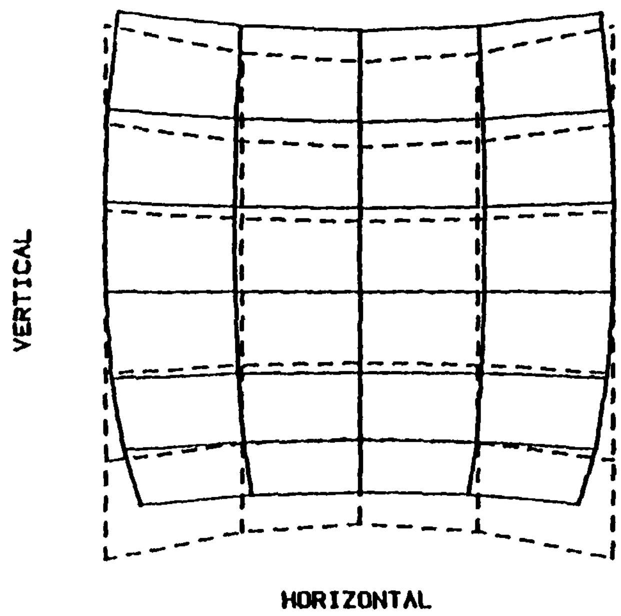
PROJECTOR LOCATION METERS: Y 2.157 Z -3.16

COMPARISON WITH
UNDISTORTED GRID



——— IDEAL DISTORTED GRID
- - - - UNDISTORTED GRID

COMPARISON WITH VERTICALLY
SCALED GRID



——— IDEAL DISTORTED GRID
- - - - VERTICALLY SCALED GRID

FIGURE 20

There is no well-defined location for projectors to achieve minimum deflection at the screen, since rays directed towards points in the cockpit do not originate from common foci in screen space. However, for the preferred collimation system design, a minimum range of vertical deflections at the screen is required if the projector is located 5.8 meters above the pilot's nominal head height.

High projector location presents three substantial sets of problems. First, there are mechanical problems associated with a projector height of 5.8 m above the pilot. This distance, plus the depth of the projector, may not be available within the simulator building. If a motion system is feasible, it will be made [illegible]re difficult by the moment of inertia of the projectors. These problems can be reduced significantly by the use of a flat mirror folding the light path between the projectors and the screen.

The second set of problems is in providing additional distortion-correction at the projector when the angle of incidence of light on the rear-projection screen is large. Figure 21 shows the distortion requirement for a single projector 5.8 m above the pilot on the collimation system axis. The plot is for the preferred system and shows the grid shape required on a flat projector object surface to a coordinate grid image 60^{0} elevation.

The third problem area is in achieving sufficient depth of field to project a well-resolved image onto the screen at a very oblique angle. All of these sets of problems are, in principle, solvable for any of the three projector types considered. But only in the case of a laser projector are the problems easily solvable by economically attractive methods.

3.4.5 Depth of Field R[illegible]quirements and [illegible]apabilities. Assuming, first, that the projector lens system is designed to focus on a flat image surface orthogonal to the projector axis, depth-of-field requirements are large. If the projectors are on a level with the horizon image at the screen, the depth of field required is 1.06 m. This figure applies to a section of screen providing 60^{0} in azimuth, in the preferred collimation system. If the projectors are set well above the horizon-image level, say at [illegible] m for straight-through projection, the depth-of-field required is [illegible].13 m.

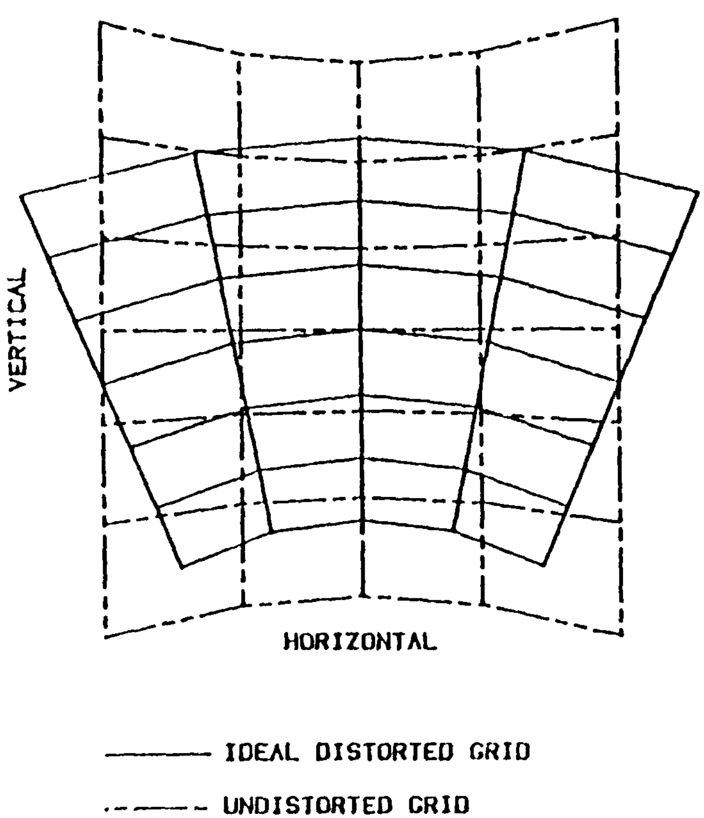
These depths-of-field are well within the capabilit[illegible] of a laser system which, at the required field angles, will provide [illegible] resolution at all throw distances between about [illegible] m and infinity. The depth-of-field of the oil film light valve, assuming three [illegible] fill the 180^{0} field, will be about 1.2 m to [illegible] m, depending on the [illegible] criterion adopted. 1.5 m defocus will blur an image [illegible], [illegible] be tolerable in the corners of a field section, [illegible] any case be good. This blur will be seen from the [illegible] spread of 4.6 arc minutes.

The depth-of-field for the [illegible] projector, [illegible] the region [illegible], again depending on the [illegible] will produce a [illegible] circle, [illegible] arc minutes. [illegible] may be acceptable [illegible].

PROJECTOR IDEAL DISTORTION,

PROJECTOR LOCATION METERS: Y 5.89 Z Ø

COMPARISON WITH
UNDISTORTED GRID



COMPARISON WITH VERTICALLY
SCALED GRID

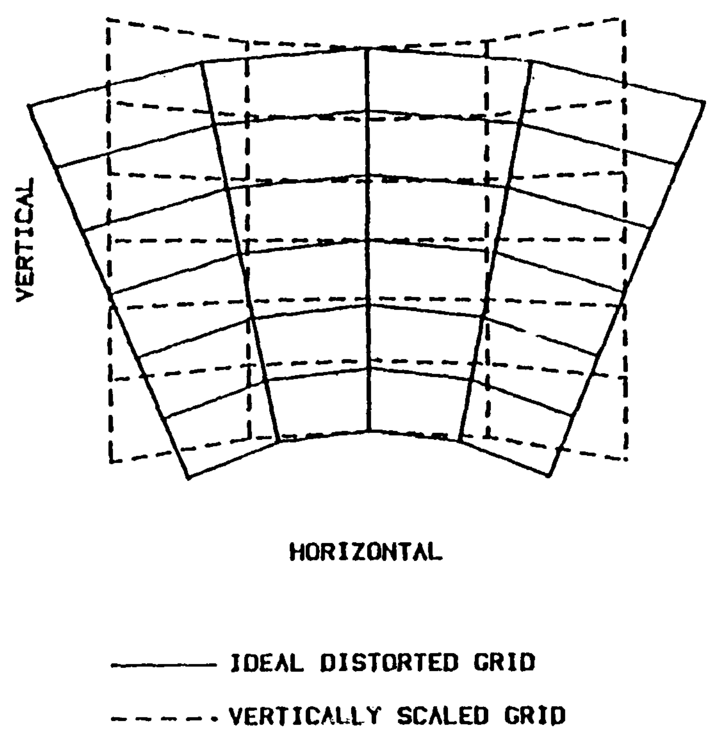


FIGURE 21

Either a laser projector or an oil film light valve may be used at any of the projector locations discussed above. In the case of the light valve set high to project through the screen at minimum deflection, there may be a marginal loss of resolution at the top and base of the field of view.

The KDP projectors present more significant problems, considering depth of field. If the projectors are located on the horizon image level, the depth-of-field requirements can be reduced substantially by designing special projector lenses to focus on a concave spherical surface, matched to the mean curvature of the screen. This presents no significant additional difficulty assuming that special lens designs will in any case be needed. Assuming correction for spherical curvature, the depth-of-field requirements for the preferred design, for a $60^{o} \times 60^{o}$ section of screen, is reduced to 15 cm, which is well within the projector's capability.

Correction for spherical curvature of the image surface is necessary but not excessive if the projectors are located well above the horizon image level. It is, in principle, possible to correct also for tilt of the image surface, by using a tilted projection lens or lens element group. However this might in practice prove very difficult because of the relatively large exit pupil.

3.4.6 Use of Oil Film Light Valves. There appear to be a number of possible methods of using this projector to achieve at least some aspects of the system specification. Two are considered to be particularly worth consideration.

3.4.6.1 Horizon Level Projection. First, light valves may be grouped around the system axis, on the horizon level, as indicated in Figure 11. This scheme is similar to the one suggested by Shaffer & Waidelich (1977). The folding mirrors are used with each of these projectors. The second mirror in each pair is curved to correct for distortion. The scheme differs from the one presented previously, primarily in that the effective locations of the projector exit pupils (their images in the folding mirrors) are set close to the axis of the collimating system. This scheme has the following advantages:

1. Good distortion can be achieved by a relatively simple curvature of the second fold mirror - cylindrical curvature only, probably produced by bending a plastic mirror.

2. Baffles can be set between projector systems to provide masking at the edges of field sections (without intermediate image formation) and also to provide improvements in contrast ratio by reducing cross-talk between projector sectors behind the screen.

The scheme requires relatively wide-angle projector lenses, but this should certainly be feasible. The lenses are likely to produce some pincushion, which could present a problem in registering field sections at the inner edges. However, the problem of pincushion distortion can be turned to partial advantage. If the projector exit pupils are separated, similar to Figure 12, this produces a relative convex curvature of the adjacent edges of field sections, due to the screen concave curvature. Pincushion distortion will partially compensate for this differential curvature. The separation of exit pupils is useful to provide finite volume for location of baffles and fold-mirror mounting structure, without vignetting at field section joints. Special screen structure would certainly be required to give brightness comparable with the specification. It is considered unlikely that a special screen will in practice give a gain factor above 2. With three light valves, this would provide a peak white brightness in the middle of each field section of about 6 foot-lamberts. In worst areas, the peak white brightness would be expected to fall to around 3 foot-lamberts.

These brightness levels are comparable to the specification.

3.4.6.2 Straight-Through Projection. Straight-through projection with light valves is feasible, at some substantial cost in development, with distortion-correction optics. A rough layout is indicated in Figure 12.

Each of these projectors operates with a curved mirror and a relay lens. The projector is fitted with wide-angle optics, in this case providing a picture 60° wide by 47° high (the usual 3:4 format). The projector is horizontal and forms an image on the surface of a curved mirror, at a distance in the region of 1 m from the exit pupil. The mirror is a section of a spheroid (elipse of revolution about the major axis) which has one conic focus at the projector exit pupil. The mirror forms a good image of the exit pupil onto a relay lens located at the second conic focus. The lens relays the image from the mirror surface to the screen surface.

The projector exit pupils and the relay lenses are all grouped around the center vertical axis of the collimation system, so that the curved mirror axes are close to this axis also.

A flat mirror is introduced to fold the three projection systems. The curved mirror, by virtue of near-symmetry on the vertical axis of the collimation system, will be expected to correct the main components of distortion produced by oblique incidence of light on the rear-projection screen. In particular, nominally vertical lines required from the light valve will now be straight and parallel. Nominal horizontals will also be straight and parallel. The major residual distortion will (as for projectors located at horizon-image level) be vertical non-linearity--variation in spacing or horizontals--and vertical scaling.

The vertical non-linearity is controllable by selection of the height at which the projection system is located. The primary non-linearity term passes through zero when the relay lenses are at a height of 3.9 m above the pilot's head height, for the preferred collimation system design. All projection-system distortion (ignoring unknown projector lens and raster pincushion) would be less than 1% of picture height for relay-lens heights between 3.6 m and 4.3 m.

It is clear that the projector system height for best distortion correction is about 1.5 m below the best height for minimum light deflection at the screen. In practice, a compromise would probably be selected, possibly at 4.88 m relay lens height. At this point, the vertical deflection required at the screen would be about 16° maximum, and residual vertical non-linearity would be about 3% of picture height.

So far, it has been assumed that simple vertical scaling of the projected picture will be carried out within Computer Image Generation (CIG) electronics. Scaling for low projector locations is fairly small, but becomes a more significant factor if projectors are raised towards the optimum straight-through projection height. The shape of the format required from the projectors is compressed vertically. This is a potential advantage using the light valve since the required output picture shape can be made to approach the normal 4:3 format, reducing the inefficiency with which three projectors may be used to fill the $180^{\circ} \times 60^{\circ}$ field-of-view.

The ideal height for relay lenses, to produce a requirement for a 4:3 format, is 5.15 m. At 4.88 m the vertical scaling factor is 0.78, which is close to ideal.

Other aberrations of the distortion-correction optics have not been analyzed. If, as proposed, the light valve projector images on the spheroidal mirror surfaces, the mirrors themselves will produce little aberration. The relay lenses will be symmetrical and have long f/numbers, so that they should also produce little aberration.

The advantage of the distortion-correction spheroidal mirror system is that it permits this light valve to be used with moderate photometric efficiency, without requiring an exceptionally difficult display screen development. Accepting a compromise between distortion correction and reduction of deflection angles at the display screen should result in a residual projection-system distortion of 3% and a screen gain of about 1.5. This gain factor would give display peak white brightness varying from about 6 foot-lamberts in the middle of three sections of the field, possibly fading to about 2 foot-lamberts at joints between picture sections (now using nearly all of three 4:3 formats).

3.4.7 Use of KDP Projectors. The basic characteristics of the KDP projector make it relatively easy to select a preferred method of use. The large exit pupil diameter, and associated small depth of field, cause difficulty in using the devices to project at oblique angles onto the screen, and to add curved distortion correction optics, while retaining good aberration correction. But the large light output of the light valves permits operation at low screen gain - so that near-horizontal projection onto the screen is more readily feasible.

The preferred method is therefore as indicated in Figure 13. Three projectors are used, each filling a 60° by 60° section of field. The central projector has its exit pupil at the vertical axis of the collimation system on a level with the horizon image on the screen. Flat mirrors are used to fold the light paths from the outer projectors, and baffles are set between the three output beams to reduce glare produced by scattered light behind the screen. The virtual images of the outer exit pupils are offset from the pupil of the central projector, as indicated. This offset, to be determined when projector lenses have been designed, will permit registration of images at picture joints on the assumption that there is some projector-lens pincushion distortion.

A screen gain of about unity will be required. This will give the specified brightness in the center of each of the three fields.

Distortion correction required at the projectors will be mainly vertical non-linearity, as indicated in Figure 18. This will preferably be produced by raster control within the light valve. There may also be a case for correcting for pincushion distortion of the projector lens, likely to be up to about 5% of picture height for the central projector, and 15% for the outer projectors with oblique incidence. This may also be done by raster control.

3.4.8 Use of a Laser Projector. A laser projector would certainly be used as indicated in Figure 10.

A fold mirror is used between projector and screen, so that the bulk of the scanner system can be low. But the virtual image of the exit pupil in the fold mirror is at 5.8 m above the pilot head level.

This gives the advantage already noted that vertical deflection angles required at the screen are minimal. In the case of a laser projector, coincidently, the height is also right for optimum distortion correction.

The laser projector will be very similar to the system presently operating at RSL's development laboratories. The line scanner will precede the frame scan system, and vertical scan lines will be produced. The device will produce a 175° azimuthal scan by continuously rotating frame scan prisms. The axis of the frame scan system will coincide with the vertical axis of the collimation system.

This method of azimuthal scan automatically corrects all azimuthal distortion, i.e., all nominally vertical lines will appear straight, vertical, and at correct separations from cockpit center. Horizontals will also be straight and parallel as viewed from cockpit center. The only distortion which need be addressed are vertical scaling and vertical non-linearity. Vertical non-linearity can be controlled by selection of the exit pupil height, and is close to a minimum for a height of 5.8 m. At this point, residual non-linearity is 0.4% of picture height.

Scaling, for the preferred arrangements, is substantial. The 60° vertical field angle scan from the cockpit will be produced by a 28° line scan at the projector exit pupil. This will require a different design for the lens system in the frame scanner (which at present delivers 60°) but the design will be easier.

The rear-projection screen gain may possibly reach a value of about 4 with a laser projector used as suggested. Assuming the laser system is engineered to output 600 lumens, this will give a peak white brightness of about [illegible] foot-lamberts. In this case, the screen luminance should be fairly uniform, since there is no azimuthal variation in power projected.

3.5 Rear-Projection Screen Fine Structure.

3.5.1 Low Projector Locations. If projectors are located on the horizon-image level, shooting near-horizontally, then the screen is required to deflect useful light through angles up to about 60°.

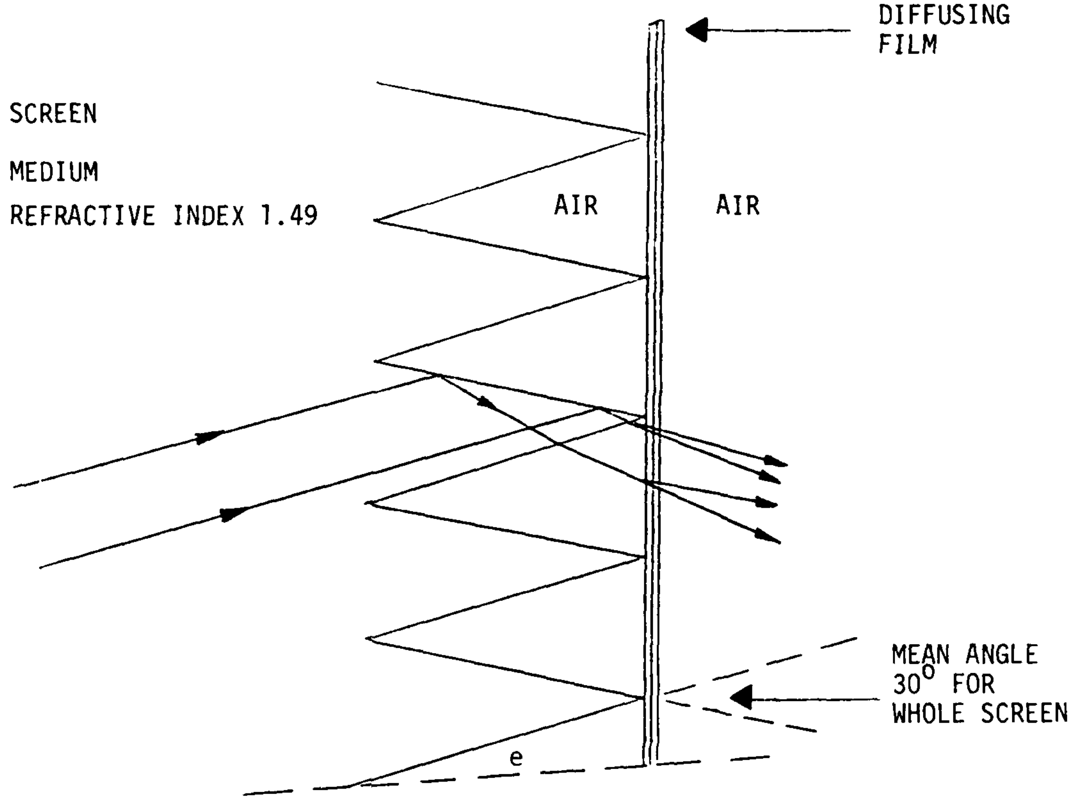
On consideration, it is unlikely that this deflection would be produced only or mainly by refracting structures. Given the relatively low refractive indices of likely screen materials, it is in theory impossible to deflect any light through 60° by refracting facets only on the outer surfaces of the screen. The deflection could be produced by steeply angled ridges on the inside of the screen. But in this case, the ridge structure was found to intercept and transmit only up to 40% of the incident light, the remainder vignetted by the lower ridge surfaces or deflected in useless directions. Thus if the inner surface is given a sufficiently powerful refracting ridge structure, there must in addition be a diffusing structure with an intrinsic straight-through gain of at least 2.5 in order to achieve an overall gain of unity. A reflecting structure could be used as indicated in Figure 22. Here deep ridges are machined or molded on the outer surface of the back-projection screen. Most of the incident light hits upper surfaces of the ridges and is totally internally reflected onto lower ridge surfaces. The lower surfaces are angled to transmit the light. The angles of both surfaces of the ridges are designed to deflect the light in the required vertical direction. The upper surface may also be slightly curved to focus light, so that there is very little vignetting.

The screen has a thin diffusing sheet material wrapped around the outer face to provide scatter over about $\pm 20^{\circ}$, in order to spread light across the full cockpit width.

This screen structure concept is preferred for potentially high efficiency. Even given practical problems in developing manufacturing techniques, it would be expected to achieve gain figures in excess of unity.

3.5.2 High Projector Locations. Given projectors located to minimize the necessary deflection angles at the screen, it is most likely that the screen will simply be formed as a clear dome in a suitable plastics material, and sprayed on the inside with a commerically available projection screen coating. In this case, gain figures up to about 4 may be expected. This gain figure could, in principle, be improved by an arrangement in which the horizontal scatter exceeds the vertical. This could be done systematically by forming refracting facets on the inside face, with vertical apexes and angles of up to $\pm 28^{\circ}$ (to deflect light to pilot and co-pilot, respectively). The faceted face would also be sprayed to add diffusion, in this case over a reduced cone angle to give higher gain.

3.5.3 Moire Fringes. A possible problem, given any non-random structure on the display screen, is moire fringe effects produced between the structure and



PITCH OF FINE STRUCTURE ORDER OF 1mm

OPTIONAL RADIUS ON UPPER FACETS: APPROXIMATELY 15 X PITCH

VALUE OF ANGLE WITH HEIGHT Y ABOVE PILOT CENTER LINE

Y m	3.78	3.23	2.65	2.16	1.65	1.28	1.0
0^{o}	-3^{o}	-3^{o}	-2^{o}	2^{o}	9^{o}	17^{o}	24^{o}

FIGURE 22 SCREEN FRESNEL STRUCTURE

the projected raster. This applies to horizontal structure used with light valves and to the vertical structure used with a laser projector.

It is likely that any non-random structure will be made finer than resolution would require in order to reduce moire fringe effects.

3.6 Comparison of Projection Systems. Table 14 attempts to summarize the likely performance of four possible projection systems described in section 3.4 above. All require some development of the projectors themselves or of screens or intermediate optics, so that many of the figures given are necessarily estimates. The intention is to give a comparison of the merits of the four approaches, on an equally optimistic basis. The laser system wins on most individual counts. It has high resolution, uniform brightness, and continuity across the whole field.

Development of the laser projector remains to be done but is already in progress, and no fundamental problems are expected, the basic capabilities of the method having been demonstrated. Speckle is a special problem of laser systems. It is likely, at 6 foot-lamberts brightness, to be desired to add a speckle-reducing device. In the context of the wide-angle multiviewer, it is expected that speckle reduction will be feasible and easily developed.

Some questions against the laser projector are associated with interfacing. The system is at present intended to accept three 100 MHz analog video signals. Digital to analog (D to A) converters for 100 MHz analog signals will be required unless the laser system is redesigned for multiple channels, which is feasible, or unless the resolution specification is reduced. Some D to A converters have been identified but development is required. A more serious question concerns the capability of the CIG system. This will be very expensive if it is to utilize fully the resolution capability of the scanned laser system. Reduction in resolution is of course feasible, but would reduce the strength of the case for a laser system.

Of the remaining alternatives, the KDP projector appears to give better overall performance. Special screen structure would be required, but would not be so difficult as for the other light valve, since less gain is necessary.

Use of the oil film light valve projector with a spheroidal distortion-correction mirror is an optically elegant and reasonably safe alternative. The advantages of light valves is that they are already available. Against this, they give low resolution, low brightness at present, and wide brightness and color variations.

Use of the oil film light valve projector with a spheroidal distortion correction mirror would entail complex mechanical structure. Also a large number of exposed optical surfaces would add to maintainability problems unless the environmental air is kept very clean. On this basis, there is a marginal preference for the lower location, although it is photometrically less efficient.

TABLE 14 COMPARISON OF PROJECTION SYSTEMS

	3 OIL FILM LIGHT VALVES LOW LOCATION	3 OIL FILM LIGHT VALVES HIGH LOCATION	3 KDP PROJECTORS	LASER PROJECTOR
Field-of-View	3 x 60° Square Windows	3 x 60° Square Windows	3 x 60° Square Windows	175° x 60°
Resolution (T.V. Lines/Ht) Field Rate (Hz)	750 60	750 60	950 60	1500 60
Projection System Distortion Raster Control Assumed	10% No	10% No	1% No	0.5% No
Peak Brightness Brightest Area Dimmest Area	 6 f. 1 3 f. 1	 6 f. 1 2 f. 1	 12 f. 1 6 f. 1	 6 f. 1 5 f. 1
Contrast Ratio	25:1	30:1	20:1	30:1
Joints Registration (arc minutes) Color Variation	2 Vertical ± 10 Some	2 Vertical ± 10 Some	2 Vertical ± 10 Some	None No Problem No Problem
Development Status	Projectors developed.	Projectors developed.	High resolution Projectors require development.	Projector still under development.
Special Problems	Special screen structure requires development. Also distorting mirror and lenses.	Moderate scale aspheric mirror requires development. Also wide-angle lenses.	Special screen required (reduced difficulty). Wide-angle lenses.	Laser speckle may be a problem.

In both locations of this projector, it is unlikely that a continuous image across the full 180^{0} will be achievable because of the presence of uncorrectable edge distortion on the individual projected images. Against this, the main advantage of this projector is that it is already available.

3.7 Summary of Projector Choice. It will be seen from the preceding sections that a clear choice of projector is not possible at this time. Basically, no projector exists that will fully meet the Air Force specification, but at least two systems are under development which have the potential of doing so. Of these two, the scan laser is the simplest to mount, has no image joints and uses a standard rear projection screen coating. Against this, the KDP system requires a complex Fresnel rear projection screen structure.

4.0 REAR PROJECTION SCREEN

4.1 General. Of the projection systems considered in section 3.0 of this report, two would require some form of Fresnel structure. The other two would require nothing more than a standard rear projection screen coating.

The Fresnel structure, if used, would be of the form shown . Figure 22. Because of the high angles required, refracting prism structure cannot be used. It is thought that reflecting prism structure as shown in Figure 22 would achieve the desired bend angles.

4.2 Screen Substrate. The screen will be made up of a basic transparent structure to which either a projection screen coating has been applied to the rear side or a Fresnel prism structure and diffusing coating applied to the front side. The basic screen will most likely be made up of acrylic plastic sections bonded together to provide the size requirement. The horizontal screen radius is approximately 3.2 meters, and the vertical screen shape is not a true radius but is approximately 2.081 meters in radius. This will require that approximately three formed sections be bonded together. This is further discussed in section 7.0 under System Mechanical Design.

4.3 Rear Projection Screen Coatings. Two vendors have been contacted who could provide or produce the diffusing layer. One method uses a spray-on type material, and the other produces a vinyl fiber layer. This would present no problem and the simplest method of application chosen within the screen gain requirements.

4.4 Application of Fresnel Structure. Some form of Fresnel structure would be required on the screen to achieve even display brightness with two of the projection techniques, one using the KDP crystal, and the other using the oil film light valve. Three techniques have been considered:

1. Machine the acrylic screen using a diamond cutter.
2. Place flexible sheets or previously lenticulated plastic on the screen surfaces.
3. Cast the Fresnel structure into the flat sheets before forming.

Casting the Fresnel structure into the acrylic screen material prior to forming is, as yet, an untried technique. It may work, but indications from vendors are that excessive shrinkage during heating and forming could be difficult to control. The extra shrinkage is caused by stress being locked in the Fresnel surface during casting.

In conclusion, machining the formed screen substrate seems to be the most promising technique, although the alternatives are still under investigation.

4.5 Additional Considerations. The screen structure could be simplified by adopting a prism angle for the whole surface. This would incur some brightness variation and loss of efficiency. The loss of efficiency is attributable to using a lower screen gain to keep the brightness variation, now introduced, to 50% with reasonable certainty. This simplified screen would then only need one tool and would work satisfactorily with KDP projectors. The overall screen gain with constant prism angle would be less than one instead of between two and three with angle variation. This means that the oil film light valve projector, with up to five times less light available than the KDP device, would need the high screen gain with variable prism angle.

For the other two projection systems, oil film light valve projector spheroidal mirror combination and the laser projector, a rear projection screen with a simple diffusing layer is all that is required. Thus, from the point of view of simpler screen construction, these two systems are preferred. As mentioned before, the oil film light valve projection system has the added complication of relay lenses and spheroidal mirrors.

5.0 COLLIMATING MIRROR VENDOR ANALYSIS

5.1 Introduction. The production of large lightweight mirrors of a quality high enough for large exit pupil displays configured for simulation has been a problem for many years. A number of vendors manufacture large mirrors of high accuracy for astronomical applications but these are extremely heavy in the present context and very expensive. At the other end of the spectrum, large mirrors are made for solar collectors, but their quality is too low, and they also tend to be heavy. A "mid quality" mirror of lightweight construction is therefore required.

On this basis, it was decided to visit a number of vendors well known in the large optical mirror manufacturing field and if possible determine whether such a mirror as required on the multiviewer was feasible. As can be seen from Section 2, the mirror for the multiviewer to meet the Air Force specification is enormous: having a 5.18 m radius and a surface area of approximately 75 m^2.

Such a mirror, if it has any chance of being fitted on a current motion system or any motion system at this time conceivable, must satisfy two criteria other than optical performance:

1. It must be extremely light - less than 4 kg/m^2.

2. It must be self-supporting because any complex support structure in itself would be an unacceptable weight and inertia.

Any mirror of this size, regardless of whether it will fit on a motion system, will have to be made in many sections. The joining of such sections is the subject of Section 7 but the problem was raised with each vendor.

The methods of mirror fabrication investigated with the various vendors were:

1. Machined and polished glass and cervit.

2. Slumped glass.

3. Machined and polished plastic.

4. Replication with lightweight bonded backing.

5.2 Glass and Cervit. A vendor was visited who works in glass and cervit, although currently doing very little work in glass. This vendor has made lightweight mirrors but constructed out of machined cervit. These mirrors are finished to a high order of accuracy for space telescopes. This vendor is not set up to deal with the type of lightweight mirror required for this project nor the accuracy (several orders lower) it requires. Also the cost would be prohibitive, accepting the fact that such mirrors could not be considered compatible with a motion base.

5.3 Slumped Glass. Several vendors make mirrors of medium quality by slumping hot glass into a mold, usually ceramic, and then either fixing it to an aluminum backing, ground and polished, or are just optically woking it without a backing. One such vendor has made a large number of medium size mirrors for monitor/beamsplittler/mirror collimating systems for flight simulation. They also have considered the use of plastic honeycomb backing as a means of keeping the weight down. This vendor indicated they had the facilities to make mirrors up to 3 m in diameter which is the right order of size for individual sections on the multiviewer.

Such mirrors using the current process would need to be around 16 mm thick and with an aluminum backing. With no support structure, a complete mirror for the multiviewer would weigh around 6,000 kg. Considering the mass alone, without reference to the inertia of such a mirror, rules it out for mounting on a motion base.

Glass mirrors perform very well and can easily have a surface quality difficult to achieve on plastic. The surface is harder and hence more durable than plastic, but fabrication is expensive and such mirrors are heavy.

5.4 Plastic Mirrors. The number of vendors in this field of manufactured plastic optics are wide and varied and they use processes from mass produced molded components to accurately ground and polished lenses, prisms and mirrors. The material used is generally acrylic, polystyrene, or polycarbonate with some specialized plastics for opthalmic applications.

One such vendor has been associated for some time in the field of medium size mirrors for simulation displays. They were therefore visited to assess the possibility of using optically worked plastic for the multiviewer mirror.

They produce mirrors, lenses, and prisms of various sizes up to 1.83 m in diameter in acrylic and polystyrene. For simulation they have made mirrors up to 1.52 m x 1.83 m. They thought this size was about the upper limit they could handle. The weight of such a mirror is about 74 kg/m^2. This would result in the multiviewer mirror being constructed from 25 to 30 sections and weighing about 5500 kg.

Although this weight of mirror is similar to the slumped glass version, the alignment of up to 30 sections and associated structure did not seem practical. The mirrors are constructed from slumped acrylic slab about 30 mm thick supported on the back surface with rectangular egg boxing using a similar thickness of acrylic slab, and the front surface is then ground and polished. The vendor suggested that the process they have adopted would give them problems with fabricating curvatures as low as the multiviewer required.

5.5 Replication. Producing optical components by replication from an accurate master falls almost into the category of section 5.4 and many vendors in the field of small to medium plastic optics, e.g., up to about 30 cm diameter, use both replication and molding dependent on the quality, type and quantity required.

With reference to replication of large optical surfaces, e.g., over 30 cm and up to 3 m, the number of vendors rapidly diminshes. Large curved surfaces are replicated by several organizations, but they are generally used on aircraft parts and microwave aerials and are of a somewhat lower quality than is required for optics in the visible part of the spectrum. The methods of replication that in general have been adopted include:

1. Epoxy resin replication from a glass or metal master, with a vacuum deposition sandwich as the separating layer.

2. Nickel deposition by electrochemical means onto a stainless steel master.

Both these techniques have been discussed at length by Shaffer and Waidelich (1977).

The main problem with the first technique is that separation becomes difficult or impossible with the size of substrates required for the multiviewer without damaging the replicate, master or both.

Nickel deposition by electrolysis onto polished stainless steel molds is a well-known technique. A well-established vendor in this field was visited whose main business is the manufacture of aspheric mirrors for xenon arc lamps. This company has made mirrors up to 0.9 m in diameter with finishes acceptable for collimated displays. The nickel is about 1 mm thick and in large sizes is supported by honeycomb material on the back. The front surface can be aluminized to improve reflection efficiency. The vendor's present facility could cope with mirrors up to 1.8 m diagonal and, with some modification, larger sizes. This vendor did not expect problems with separation of larger sizes.

The main drawback to the whole process is the cost of the initial stainless steel master which requires an optical finish as good as that required on the nickel replicate. An added difficulty is that the master is necessarily convex, and so any shape evaluation is difficult without large interferometers, or else is done by test replication. Test replication is the technique used by the vendor currently.

If such mirrors could be made large enough and self-supporting, then one of the size suitable for the multiviewer would weigh about 1000 kg.

A third technique for replication of large mirrors is the one being currently pursued, and is almost an extension of the process described previously (epoxy application) except the separating medium itself forms parts of the mold shape.

A number of trial replications have been carried out using an epoxy glass fiber reinforced honeycomb construction with a resultant weight of 6 kg/m^2. Further development is continuing before the process is completely defined. Results so far have indicated that its surface finish and durability are better than for optically worked acrylic and are in fact almost comparable with those for glass. Mirrors 3 m by 1.83 m have been made with no identifiable separation problems. Sections of this size would be suitable for the multiviewer.

The most expensive part of the process is the original manufacture of the mold, although one advantage to the process is that the mold surface need not be optically finished.

5.6 Summary of Mirror Fabrication Techniques. Table 15 summarizes the mirror fabrication techniques considered as candidates for the multiviewer.

Some other techniques for producing mirrors have been used or tried with varying degrees of success such as explosion forming and spinning baths of epoxy during curing. None were felt suitable for the multiviewer except those summarized in Table 15.

From Table 15, the epoxy replication with glass fiber and honeycomb looked the most promising and was pursued for the multiviewer. On this basis, the mirror-joining techniques were confined to the replicated mirror process.

TABLE 15 SUMMARY OF MIRROR FABRICATION TECHNIQUES

Method	Weight	Remarks
Slumped Glss	80 kg/m^2	High quality surface finish, not self-supporting, could not be fitted on a motion system
Replicated Nickel	13 kg/m^2	Good quality surface finish, could possibly be self-supporting - too heavy for a motion system
Replicated Epoxy/ Glass Fiber/ Honeycomb	6 kg/m^2	Good quality surface finish, supporting, still too heavy/ for a motion system but more development on weight reduction may improve

6.0 FABRICATION AND ASSEMBLY OF MIRROR SECTIONS

The Multiviewer collimating mirror will need to be made in at least 18 sections. The largest section will be about 2.7 m x 1.7 m situated around the top of the mirror, and the smallest about 2.1 m x 1.7 m around the bottom. The technique recommended for producing these sections is by replication. The most likely other alternative is slumped glass. Since the mirror is spherical, only one mold is required, which would be the most expensive part of the process.

6.1 Abutment of Mirror Sections. The mirror sections will need to be mounted in a fixture for abutment. This fixture will necessarily need to be as large as the final completed mirror. A schematic of a suitable fixture is shown in Figure 23.

The adjoining sections are first aligned in the fixture by using a point light source at the nominated center of the optical sphere. Each section of mirror will produce its own image of the light source in the proximity of the center. Since the mirror system will cover 180^{0} as seen from the light source, a system similar to Figure 24 will be required. Not all the images will be available at any one time, but as the light source system is turned on a turntable, each section and the joint with the next section will be visible. A rear projection screen with a graduated circle graticule will be positioned over the center of the turntable at the center of the sphere.

Starting with the mirror section nearest the center of the system, this is aligned using the six-degrees-of-freedom adjustment on the back of the section and is moved to give the smallest image of the light source at the center of the graticule. An adjacent section is then moved to position its image over the first with minimum gap between the two sections and minimum step between the two surfaces. Ideally, the gap should be less than 1 mm at its widest point. An arc minute would represent a gap of about 1.5 mm as seen from the pilot eyepoint, so there is little point in trying to make the gap much less than this, since it will always be seen as a line. Once the gap and alignment of the two adjacent sections are satisfactory, then the operation is repeated with all sections adjacent to the first one.

Each section is uniquely bolted to each adjoining section in the fixture, thereby allowing disassembly and reassembly in the simulator environment without further alignment.

The arrangement of the sections has not yet been decided, two alternatives being shown in Figure 25. The offset arrangement is preferred since only three surfaces have to be aligned to each other instead of four. The samples have been aligned using the offset arrangement. Alternatively, a hexagonal system could be considered, but this leads to a number of odd shapes around the edge of the completed system.

6.2 Fabrication and Assembly of the Demonstration Samples. Three samples of replicated mirror have been produced. The individual sizes of the samples were 0.4 x 0.3 m. These samples were made on an existing mold

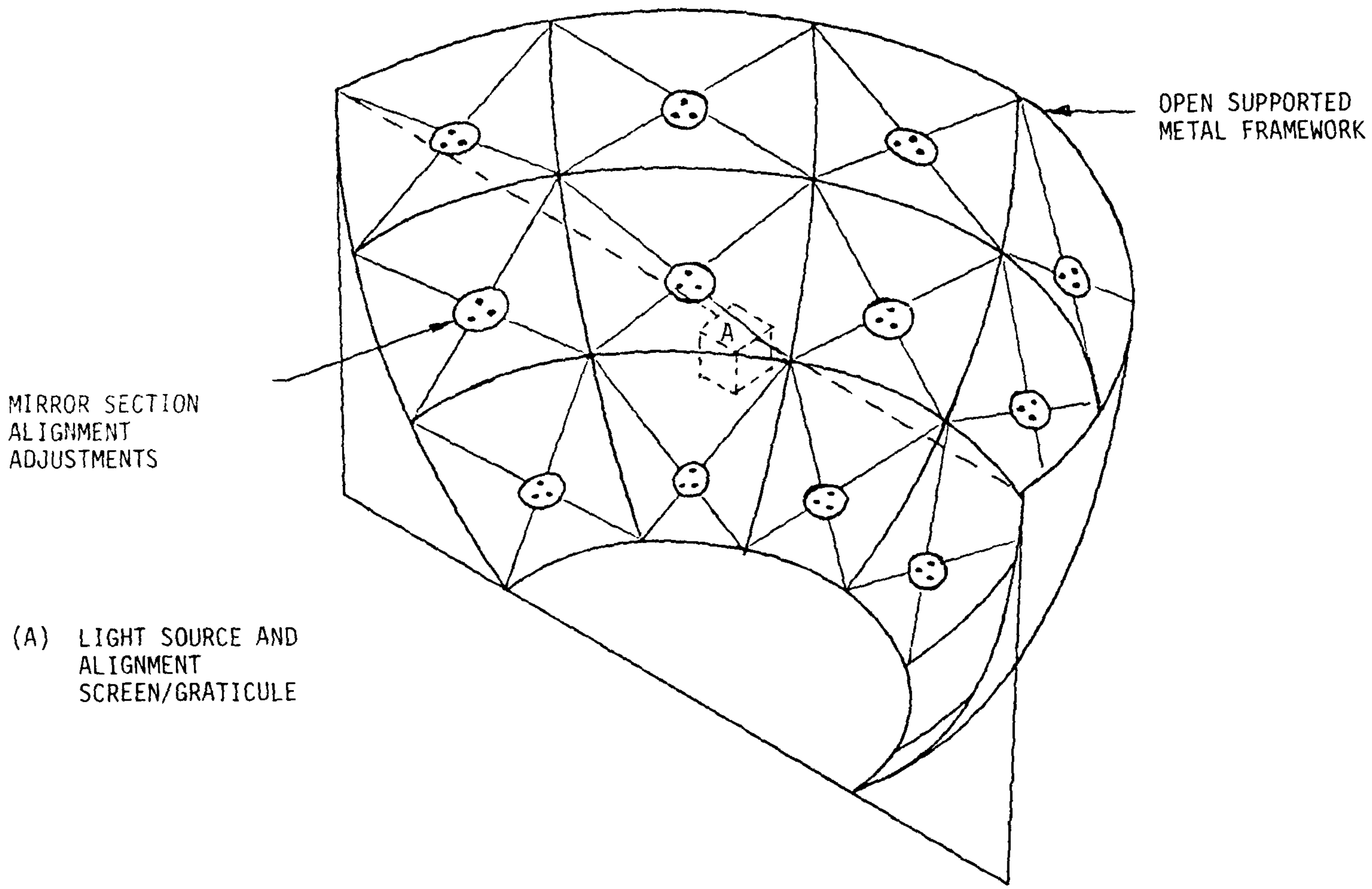


FIGURE 23 MIRROR ALIGNMENT FIXTURE

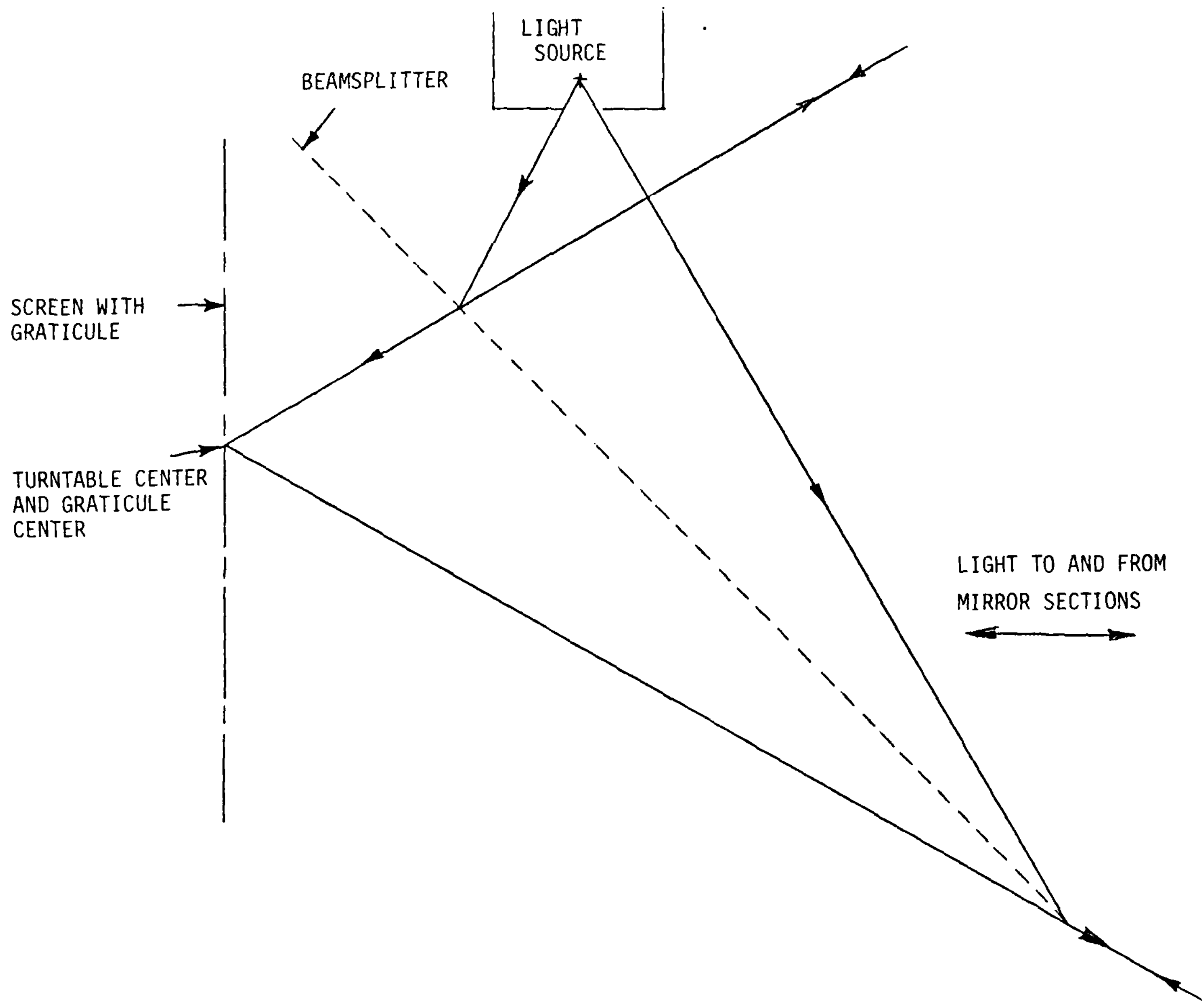
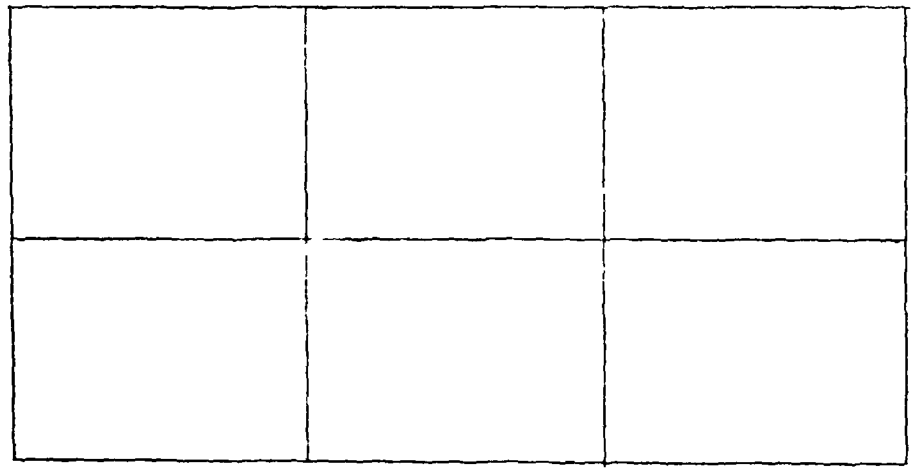
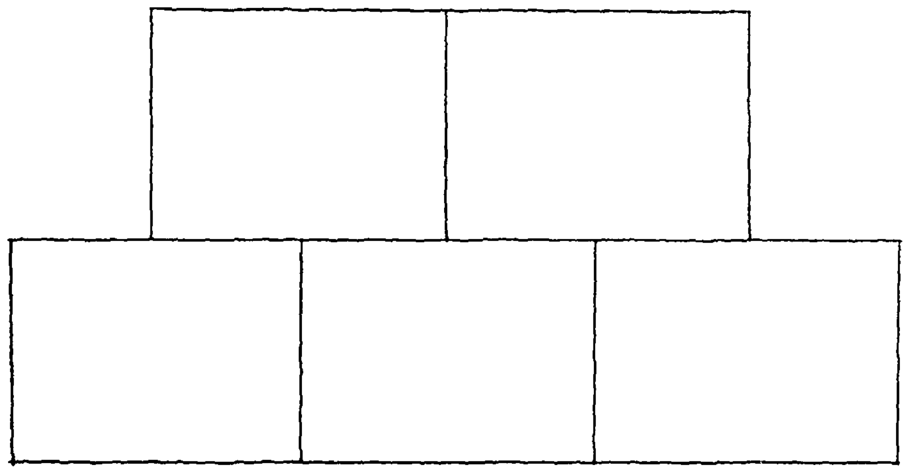


FIGURE 24 MIRROR SEGMENT ALIGNMENT DEVICE



IN LINE



OFFSET

FIGURE 25   MIRROR SEGMENT ARRANGEMENTS

surface with a nominal 3 m radius of curvature. Although the samples were somewhat smaller than the proposed section sizes for the full size mirror, the abutment techniques are identical. The surface geometry of the samples was not to the standard required for the full size section but, in this case, was partly a function of the mold surface used.

The samples do, however, demonstrate the abutment technique and give an indication of the size of gap between sections. The gap is of the order of 1 mm.

The arrangement of the sample section for abutment was as depicted in Figure 25 offset method.

7.0 SYSTEM MECHANICAL DESIGN

7.1 Introduction. A preliminary mechanical design for the multiviewer has been completed and a side view of this is shown in Figure 1. A standard B-707 cockpit and Rediffusion Simulation, LTD. integrated floor structure are also shown to indicate how such a system might be mounted on a motion system. This was done to assess the compatibility of the system with a standard motion system. The inertia of the system substantially exceeds the motion system capabilities in all axes, especially in yaw, even when making use of the self-supporting characteristics of the mirror and use of a very lightweight support structure. The yaw moment of the mirror alone, without support structure, is equal to the total yaw moment of a complete civilian aircraft simulator.

Some calaculations of inertial moments are indicated in Figure 1 for completeness but, for the reasons given previously, it was decided to abandon the idea of mounting the Multiviewer on a motion system. No doubt a motion system could be built to support the Multiviewer and allow reasonable accelerations to be achieved for simulating a wide-bodied jet, but the design and specification of such a system is outside the scope of this report.

On this basis, the following delineation of the design assumes a fixed base simulator.

7.2 Mounting of the Collimating Mirror. The collimating mirror is assumed to be made out of sections of epoxy/glass/fiber/honeycomb material, manufactured and prealigned in a fixture as described in section 6.0. Each section will be surrounded by a collar made in the fixture such that it will come into intimate contact with adjoining sections. Handling strong points will be built into each section. Because of the pre-alignment technique, the sections, once aligned, can be disassembled and rebuilt on the simulator.

The mirror will be supported from a central archway tower over the simulator cockpit. A steel cable with tensioners will pass around the top of the mirror, and this will be taken back to the tower and down to the base.

The mirror will be self-supporting in the vertical section and anchored at the bottom onto a base. This base will be about 1 m deep and placed, as shown in Figure 1 for the integrated floor structure, only at ground level.

The central tower will be an aluminum alloy double skinned box structure (basically a box within a box). Each wall of the box will be double skinned. With reference to Figure 1, one wall will be the Main Traverse Frame and the other the Straddle Box Frame. Each wall will be about .1 m thick and capable of being stripped down for transportation. There will be a central archway through the fabrication for positioning the simulator cockpit.

7.3 Projector Mounting. The projector will be supported on the top face of the central tower. Figure 1 shows a Scan Laser Projector mounted on top, but a similar system could be used for the other projector types.

Ladders will be mounted on the outside of the tower to gain access to the projector for maintenance. Safety rails will be mounted around the outside of the platform supporting the projector.

The upper plane fold mirror (only required for the Laser Projector) will be simply supported from a vertical extension of the Main Traverse Frame cross braced back to the rear Straddle Box Frame. This mirror will be made by the same fabrication process as the collimating mirror.

7.4 Rear Projection Screen Mounting. The mounting of the rear projection screen poses the most severe problems of any other component in the system. The screen will almost certainly have to be made in sections and pre-fabricated prior to installation to minimize the effects of joints as described in section 4.0.

The screen can only be held around the edge by nature of its function and will have to be cantilevered back to the central tower with all structure staying outside the light path. The bottom edge of the screen will be supported at the base of an aluminum fabricated cone. The solid floor will contain the screen in the horizontal direction and the sloping side acts as a vertical support. These sections are indicated on Figure 1 as the sway and pitch constraints, respectively. The top of the screen will be tied back to the edge of the fold mirror by using lightweight honeycomb sheets which will also act as light barriers.

Exactly how much support the screen will require prior to installation on the simulator is unknown at this time.

Because of its size, it cannot be handled without some support. From this consideration, the screen will probably be joined to the aluminum cone during its fabrication and transported as one piece. The top and sides of the screen could be held with aluminum collars and then cross-braced for transportation. The cross-bracing will then be removed after the screen has been assembled in position on the simulator.

7.5 Light Barrier. Most of the structure will, in itself, act as a barrier to ambient light except the area between the top of the mirror and the top of the rear projection screen. There are numerous ways this could be done using various flexible fabrics, but the method favored is to construct a rigid truncated pyramid out of two thin sheets of aluminum with about 2 to 3 cm thick expanded polystyrene in between. This type of approach will cause the least stress on the optical components due to sagging.

7.6 Alignment. The projector will have the capability of adjustment in pitch and roll for positioning the image of the rear projection screen in the case of the Laser Projector. The other types of projectors will require adjustment capability in all six degrees of freedom, particularly the oil film light valve type. The position of the rear projection screen will be fixed.

Adjustment of the mirror position has been considered but judged to be impractical. Considering the size of the mirror, it could be positioned several centimeters from its design position without noticeable effect on display geometry or vergence errors. The most noticeable effect will be rotation errors, particularly pitch. These errors can be removed by adjusting the projector position. A tolerance of ± 1 cm on the mirror position could be accommodated, and this should be well within the capabilities of the fabrication techniques to be employed.

8.0 TRADE-OFF ANALYSIS AND CONCLUSIONS

8.1 Trade-Off Analysis. To meet the AFHRL specification for a 180° x 60°, collimated, large exit pupil display requires a collimating mirror of at least 5.18 m radius. Considering this size and the attendant mechanical assembly and building size problems, it was thought a useful exercise to identify how a reduced mirror radius would affect the basic system performance, while maintaining distortion at a reasonable level. This exercise was also carried out with a view to defining a system compatible with standard six-axis motion systems.

The results of this study are depicted in Table 16. The two systems of greatest interest in this respect are the system with a 180° x 50° field and the one with a 180° x 40° field.

It is conceivable that the 180° x 50° system could be fitted to a motion system, but the base frame would need to be moved to the most advantageous position with respect to the hydraulic rams, i.e., the system is compatible, but not necessarily retrofitable.

Reducing the vertical field still further to 40° reduces the mirror radius to between 3 and 3.5 m and results in a system capable of being retrofitted on most existing simulators on six-axis motion systems. Such a system would be compatible with the downward "out-of-the-window" field of most Boeing aircraft. The Lockheed "C-130 and C-5," particularly the C-130 with foot windows and large pilot separation, could be deficient with such a small system. Air refueling would also require a larger vertical field of view.

The significant performance parameters that affect mirror size are vertical field of view and vergences, mainly dipvergence. Reducing the pilot separation on the 60° system does not significantly affect mirror size.

The argument here is that a basic system for a 180° x 60° field and a 1.22 m separation of pilots has been designed. Should a display system be required for a simulator of a particular aircraft type and defined operational role, then it would be advantageous to optimize the display system to suit. For a research simulator, however, perhaps the full 180° x 60° is needed.

8.2 Conclusions. A collimated display system has been designed that will meet the AFHRL optical specification for a 180° x 60° field of view, and large exit pupil. The distortions are within the tolerances specified, and it is considered that should such a system be built, it would prove to be a useful training device. The components within the optical system are exceedingly large in comparison to normal simulator visual systems and will require fairly unique manufacturing techniques to ensure cost effectiveness.

It is not considered feasible to fit this display system to a standard motion system. On this basis, some ideas as to what size and what reduction of specification would achieve a display without this constraint has been discussed.

TABLE 16 TRADE-OFF EXERCISE

FIELD-OF -VIEW (DEGREES)	DISTORTION PERCENT PICT. HT.	LIGHT CONVERGENCE	DIPVERGENCE	PILOT HEAD LOCATION OFF AXIS (METERS)	RADIUS (METERS)
180 x 60	WITHIN 5%	* AT -30% FORWARD $\pm$2.5 MR	WITHIN 3MR	.61	4.57
180 x 60	WITHIN 5%	WITHIN 3MR	* UP TO 4MR RIGHT OF CENTER	.61	4.57
*180 x 50	WITHIN 5%	WITHIN 3MR	WITHIN 3MR	.61	4.5
180 x 60	WITHIN 5%	WITHIN 3MR	WITHIN 3MR	* .53	4.94
*180 x 40	WITHIN 5%	WITHIN 4MR	WITHIN 3MR	* .53	3.0
180 x 60	WITHIN 5%	WITHIN 3MR	WITHIN 3MR	.61	5.18

* INDICATES PARAMETER OUTSIDE SPECIFICATION

TABLE INDICATES HOW AND AT WHAT RATE PERFORMANCE PARAMETERS ARE AFFECTED BY MIRROR RADIUS. RATES INVARIABLY INCREASE WITH REDUCTION OF MIRROR RADIUS SO PARAMETER WAIVERS CANNOT BE GROUPED AND A PRORATA MIRROR RADIUS REDUCTION APPLIED.

The major manufacturing challenge is the fabrication of the collimating mirror. Either slumped glass or replication could be used if the system is to be fixed base. Replication, however, is still considered to be the most cost effective way. Such mirrors, although plastic, are capable of being cleaned and maintained using the same techniques practical for glass optics.

Three samples have been fabricated and butted together, using the same technique as would be used for the full size mirror. These were made on a mold surface of a size comparable with the full size mirror sections, but not the same shape. The sample sizes were each 0.4 x 0.3 m, but sufficiently large to demonstrate edge matching. The gap between these sections was nominally 1 mm as expected.

There is no available projector capable of meeting the image resolution requirements and still be compatible with the optical system. Such projectors are under development, and there is no technical reason to assume that such a device could not become viable. Whether such a projector will be built in the near future will depend on funding and/or market potential.

The projector currently available that comes nearest to meeting the Multiviewer requirements is the light valve device. One other projector, the KDP device, could also be considered, but has a lower vertical resolution. It would, however, have no diffiiculty in meeting the image brightness requirement.

This phase of the Multiviewer program has been an interesting and challenging exercise into how far this type of display system can be stretched and remain technically viable. It is doubtful whether larger fields of view or tighter distortion characteristics could be practically achieved with this type of display. In these cases, large domes using direct projection or novel Area-of-Interest type displays probably offer the best solution.

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